Outlining the afforestation and reforestation process chain for carbon dioxide removal

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Abstract

Afforestation and reforestation (A/R) are widely promoted as carbon dioxide removal (CDR) strategies, yet their climate change mitigation potential depends not only on forest establishment but on whether carbon removals remain additional, durable and verifiable over time. Here we conceptualize A/R as a 'process chain' of coupled decisions, from site selection and establishment pathway, through stewardship, carbon storage, as well as monitoring, reporting, and verification, in which choices made at one stage constrain or shape carbon outcomes at subsequent stages. Our synthesis shows that the climate effectiveness and credibility of A/R-as-CDR are highly contingent on context: carbon sequestration rates vary across climates, soils, species and management regimes, while the durability of stored carbon can be threatened by wildfire, drought, pests, and land-use change, with the latter often driven by shifting governance conditions. Even when tree cover increases, claimed carbon removals can also be undermined by failures in governance and social legitimacy, biophysical and operational readiness, as well as accounting and verification. We therefore argue that A/R should be evaluated not by hectares planted, but by whether it delivers additional, measurable, verifiable, and durable net carbon removals from the atmosphere under conditions of social legitimacy and accountable governance. This framework reveals how risks interact across stages, how failures propagate through the system, and where interventions can improve the durability and credibility of net removals. A/R can therefore contribute meaningfully to climate mitigation, but should complement, rather than substitute for, rapid and sustained emissions reductions.

Keywords: Afforestation and reforestation; carbon dioxide removal (CDR); process chain; carbon durability; monitoring, reporting and verification (MRV).

1. Introduction

Anthropogenic climate change is unequivocally driven by the accumulation of greenhouse gases (GHGs) in the atmosphere, primarily from fossil fuel emissions, industrial processes, and land-use change (Friedlingstein et al., 2026). The physical science basis synthesized in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) notes that continued emissions translate into continued warming, and that the resulting impacts generally scale with cumulative carbon dioxide (CO_2) emissions (IPCC, 2021). Once emitted, CO_2 persists in the atmosphere for centuries to millennia, committing the climate system to long-lasting change (IPCC, 2021). Within this framing, climate stabilization is fundamentally a two-part problem which encompasses finding solutions for: (i) rapidly reducing gross emissions toward near-zero, and (ii) addressing residual emissions from hard-to-abate sectors and the legacy CO_2 that has already been accumulating in the atmosphere. Limiting global warming to below 2^oC thus requires not only rapid and sustained reductions in gross emissions, but also carbon dioxide removal (CDR), that is, the anthropogenic removal of CO_2 from the atmosphere followed by its durable storage, to counterbalance residual emissions from hard-to-abate sectors (IPCC, 2021, 2022a). Integrated assessment models aligned with the Paris Agreement temperature goals typically assume substantial deployment of CDR. However, the scale of reliance on CDR for climate mitigation is not a constrained parameter. As Smith et al. (2016) noted, large-scale CDR faces biophysical, ecological, and governance constraints, including land and water competition, nutrient demands, and societal trade-offs. The central challenge therefore extends beyond establishing the need for CDR to determining how it can be designed and governed to deliver environmentally sound, socially legitimate, durable, and credibly verified removals. For afforestation and reforestation (A/R) in particular, this challenge is best understood not in terms of tree planting as a stand-alone action, but as a coupled process beginning with the choice of an ecologically and socially appropriate pathway to forest establishment or recovery, including natural regeneration where feasible, and extending through establishment, growth, management, permanence, and verification. This process-chain perspective provides the organizing logic for the sections that follow: each stage conditions whether long-term carbon storage can be established, retained, and credibly verified. While our analysis focuses primarily on A/R interventions involving tree planting, we regard planting as one possible means of establishing forest cover, rather than an end in itself.

1.1. Carbon dioxide removal (CDR)

CDR encompasses anthropogenic activities that remove CO_2 from the atmosphere and durably store it in geological, terrestrial, oceanic, or product reservoirs (IPCC, 2022a). This definition distinguishes removals from avoided emissions and foregrounds permanence (referring to continued retention of stored carbon over the crediting or management period and beyond) as a core criterion for climate effectiveness (IPCC, 2022b). CDR methods differ in both the processes through which CO_2 is captured from the atmosphere and the carbon pools in which it is subsequently stored. Atmospheric CO_2 may be captured through biological, geochemical, or engineered chemical processes, while storage may occur in vegetation, soils and sediments, geological formations, long-lived products, or marine sediments. Individual CDR methods represent different combinations of these capture and storage processes, and some involve transfers through multiple carbon pools before reaching their longer-term storage reservoir (Smith et al., 2024). Within this framework, A/R relies on biological CO_2 capture through photosynthesis, with carbon stored in vegetation, soil, and other product pools. Its carbon-storage dynamics and associated permanence risks therefore differ

substantially from methods that transfer captured carbon into geological or mineral storage pools, that generally provide longer storage timescales. While rapid decarbonization remains the primary mitigation priority, CDR is increasingly framed as a complementary mitigation measure, principally for counterbalancing residual emissions. Land- and ecosystem-based CDR methods, including A/R, are featured prominently in current mitigation pathways (Babiker et al., 2022; Nabuurs et al., 2022; Smith et al., 2024) and have comparatively well-established implementation and accounting practices. When appropriately designed and adapted to local conditions, they may also provide co-benefits such as watershed protection, rural livelihood support, and biodiversity conservation (Griscom et al., 2017; Erbaugh and Oldekop, 2018; Ota et al., 2020; Nabuurs et al., 2022). Their familiarity and potential co-benefits may also contribute to greater social acceptance in some contexts than less established CDR approaches. However, their deployment is constrained by competition for land, water, and human resources, as well as governance and regulatory challenges, risks to the permanence of CO_2 storage, and uncertainty in monitoring, reporting, and verifying (MRV) the amount of CO_2 stored (IPCC, 2019; Mace et al., 2021). These constraints are not merely implementation frictions: they directly affect whether the resulting removals are additional, durable, and credibly quantifiable. Integrity in land- and ecosystem-based CDR thus depends on the biophysical potential as well as the robust process-chain design and implementation, suitable regulation, and credible MRV to quantify and verify carbon removals and their permanence and, where possible, inform management decisions that safeguard or enhance CDR outcomes (Mercer et al., 2024).

1.2. A/R as a CDR pathway

Afforestation (establishing a forest on land not recently forested) and reforestation (re-establishing a forest on recently forested land), hereafter collectively called A/R, are among the most widely implemented land-based CDR approaches. A/R is used here specifically for forest establishment or recovery and should not be interpreted as synonymous with ecological restoration, which can encompass a broader range of ecosystems, objectives, and reference conditions. Currently, A/R provides about 1.9 billion tons of CO_2 removals each year; together with harvested wood products, A/R makes up 99.9% of all current global CDR (Pongratz et al., 2024; Smith et al., 2024). Through photosynthesis, trees assimilate atmospheric CO_2 and incorporate the carbon into living biomass. Some of this carbon is subsequently transferred from living biomass to dead organic matter and soils through processes such as litterfall, root turnover, and tree mortality. Additional storage is possible in harvested wood products depending on management and project boundaries. At global scales and over the historical time period, existing forests have widely functioned as a substantial net carbon sink, offsetting a meaningful share of anthropogenic emissions, albeit with strong spatial variability and disturbance sensitivity (Pan et al., 2011). Assessments of land- and ecosystem-based mitigation similarly highlight that well-designed reforestation can make a meaningful contribution to climate change mitigation, but only in ecologically appropriate settings and under governance conditions that avoid reversal (referring to carbon release from previously accumulated biomass or soil carbon), leakage, and land-use conflict (Griscom et al., 2017; IPCC, 2022a). However, the CDR potential of A/R differs markedly across contexts because carbon sequestration rates, mortality risks, and soil responses depend on climate, soil type, species choice, and management (Laganière et al., 2010). In other words, similar A/R intervention can generate very different carbon outcomes depending on where they occur, the reforestation approach used, the species and stand composition that develop, climatic

conditions, and how the forest is managed through time. Moreover, the permanence of the biomass carbon storage is uncertain: wildfire, drought, storms, and pests can release accumulated forest carbon stocks (Anderegg et al., 2020, 2022), with climate-change-induced increases in the intensity, frequency, and duration of such events (Dye et al., 2024). Additionally, poorly sited or weakly governed A/R projects can also generate trade-offs involving biodiversity, water availability, food security and other outcomes (IPCC, 2019). These aspects and potential limitations require A/R to be approached as a systems intervention rather than a monolithic solution. Its CDR value depends on the cumulative effects of decisions and carbon flows over time, including the durability of stored carbon and emissions associated with implementation through life-cycle assessment (LCA).

1.3. Positioning A/R within CDR portfolios

A/R-as-CDR should be understood as a complement to, rather than a substitute for, rapid emissions reductions. CDR is likely to be required to counterbalance residual emissions (IPCC, 2022) and, in some pathways, to help reverse temporary temperature overshoot (Geden and Reisinger, 2025; Reisinger et al., 2025). However, reliance on uncertain future removals cannot compensate for delayed mitigation, particularly for biologically mediated CDR such as A/R, where carbon accumulation is gradual and stored carbon remains exposed to disturbance and reversal. A/R occupies a distinctive position within the CDR portfolio because it is biologically mediated, land-intensive, and embedded in inhabited landscapes, making carbon outcomes closely coupled to ecological conditions, governance, and societal priorities. Importantly, ecological benefit should not be conflated with carbon-crediting integrity: an A/R intervention may provide local environmental value even where its removals remain uncertain, reversible, or weakly attributable to support high-integrity CDR claims. Conversely, poorly designed or implemented interventions can generate unintended ecological and social harms, including ecosystem conversion, biodiversity loss, reduced water availability, or adverse livelihood impacts (Di Sacco et al., 2021; Fleischman et al., 2020; Holl and Brancalion, 2020). Misaligned incentives or weak governance can further lead to inequitable benefit sharing or undermine permanence (IPCC, 2019). The imperative is therefore not simply to expand tree cover, but to design A/R interventions that are ecologically appropriate, socially legitimate, and carbon-accountable over multi-decadal horizons (Reek et al., 2026; Heilmayr et al., 2020)

1.4. From concept to implementation: the A/R process chain

Although A/R is frequently framed as tree planting, its CDR value emerges from a multi-stage process chain. It begins with pre-implementation screening of factors such as governance, tenure, opportunity costs, and environmental risk; proceeds through site and species selection, forest establishment or regeneration and subsequent management and disturbance response; and may extend downstream to biomass and product pathways. MRV is also integrated across these stages to quantify carbon outcomes, uncertainty, leakage, and reversals and to support credible removal claims. Decisions at one stage can thus constrain outcomes at later stages, making cross-stage dependencies central to the effectiveness of the overall CDR intervention.

The process-chain framework synthesized in this review (Figure 1) was developed through iterative expert engagement as part of the "CDRatlas" project (`https://cdratlas.org`, last access: 11 November 2026), including structured workshops and consultations with specialists spanning forestry, restoration ecol-

ogy, socioeconomic and governance aspects, carbon accounting, assessment, and carbon-market design. These discussions were used to identify integrity-critical decision points, common failure modes, and dependencies across stages of the A/R process chain. The resulting framework integrates ecological, operational, socioeconomic, governance, and accounting dimensions and structures the review from site and species selection through establishment, management, downstream product pathways, carbon-storage dynamics, and MRV. In doing so, we outline how decisions made at successive stages influence carbon accumulation, durability, and the credibility of resulting removal claims, with the broader aim of supporting robust A/R deployment within Paris-aligned mitigation pathways (IPCC, 2019, 2021).

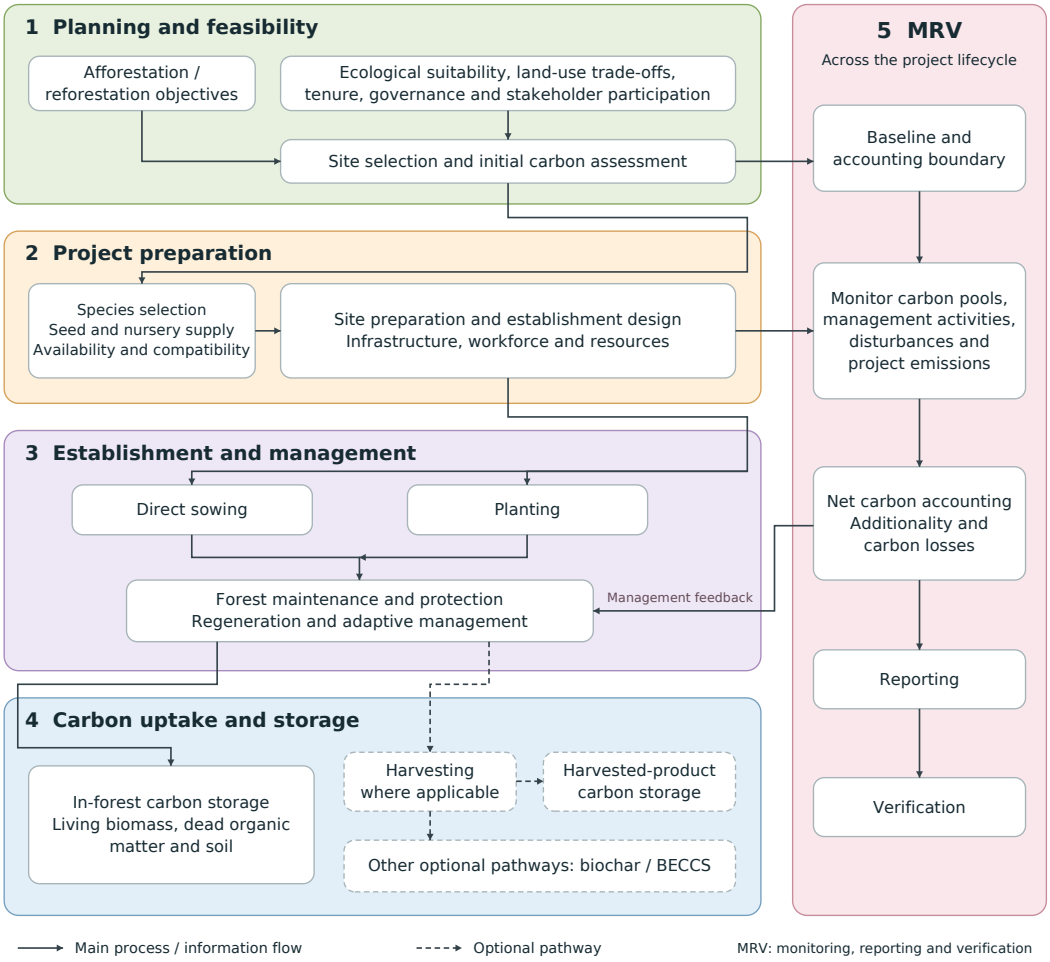


Figure 1. Schematic overview of the afforestation and reforestation process chain for carbon dioxide removal. Colored groups distinguish planning, preparation, establishment and management, carbon uptake and storage, and monitoring, reporting and verification (MRV). Dashed arrows and boxes indicate optional pathways.

The framework is intended as a diagnostic and decision-support structure rather than an exhaustive catalogue or prescriptive protocol. It can be used to organize project screening and due diligence, identify upstream constraints that may compromise later carbon outcomes, compare alternative establishment and management pathways, and target monitoring toward integrity-critical stages and interfaces. It can also provide a common structure for assessment and decision-support applications, including the Carbon Dioxide Removal Atlas (CDRatlas).

This review focuses on the A/R intervention and the sequence of decisions that determines its carbon outcome. These project- and landscape-level processes contribute to national and global A/R deployment, but scaling is not simply additive: national policies, land and commodity markets, carbon prices, international trade, and broader economic development can alter land-use incentives, opportunity costs, leakage, and counterfactual trajectories. The process-chain framework can therefore identify ecological, operational, social, governance, and accounting conditions that constrain individual interventions and their deployment at scale, but it does not itself model economy-wide land-use responses, international market feedbacks, or the optimal deployment of A/R within national or global mitigation portfolios. These larger-scale factors therefore constitute boundary conditions that can modify incentives, feasibility, and carbon outcomes throughout the chain.

2. Site selection

Site selection for A/R-as-CDR pre-configures all later stages of the process chain: it shapes which species are viable, how difficult establishment and maintenance will be, how high reversal risk remains, and whether subsequent MRV can support credible claims. Consistent with IPCC assessments, land-based mitigation potential, including A/R, is highly context dependent and constrained by climate risks, land competition, and governance and regulatory conditions, making early screening essential for both feasibility and integrity (Mace et al., 2021; Nabuurs et al., 2022). At this stage, the main question is not simply whether trees can grow, but whether carbon removals within an entire forest ecosystem (vegetation and soil) can be established, maintained, and sustained over time scales relevant to climate mitigation. Site-selection criteria are not independent dimensions; existing multidimensional integrity and sustainability frameworks similarly emphasize interacting ecological, social, governance, and carbon-accounting considerations (Dooley et al., 2024; Nabuurs et al., 2022). In the process-chain framework used here, these considerations are organized according to when they constrain decisions and outcomes rather than treated solely as parallel categories; consequently, issues such as biodiversity, tenure, livelihoods, equity, economic feasibility, and benefit-sharing may recur across several stages of the chain.

2.1. Biophysical suitability

The first screening question is whether the site is ecologically appropriate for forest establishment or recovery and whether it can support additional carbon storage over the relevant time scale. Biophysical suitability depends on the interaction of current and future climate, water availability and hydrological regime, soil depth, texture, fertility, drainage and salinity, topography and exposure, existing vegetation, prior land use, and pre-existing soil and biomass carbon stocks (IPCC, 2019; Nabuurs et al., 2022). Combined, these conditions define the environmental envelope within which selected tree species can establish, grow, and persist over the full life span. These factors influence the establishment success and growth rates, as well as the size and trajectory

of different carbon pools and the likelihood that additional carbon can be retained through time (Anderegg et al., 2020, 2022). Screening should also consider whether forest cover is consistent with the site's natural or historical ecosystem state: naturally open ecosystems such as grasslands, savannas, peatlands, or wetlands may be biophysically capable of supporting planted trees but inappropriate for A/R because afforestation could reduce biodiversity (Veldman et al., 2019) and water availability, or contribute to soil salinization (Farley et al., 2005; Jackson et al., 2005). Carbon-rich wetlands and peatlands likewise require particular caution because drainage or other hydrological alteration can jeopardize large pre-existing soil-carbon stocks (IPCC, 2019). Future suitability is equally important, because a site that supports a given forest type under present conditions may become increasingly marginal under warming, altered precipitation, or changing disturbance regimes (Anderegg et al., 2020, 2022). Accordingly, biophysical assessment should consider both present growing conditions and their expected trajectory, including risks (see Sec. 2.3). Sites that require substantial drainage of carbon-rich soils, persistent irrigation, or other intensive resource inputs may therefore be unsuitable for A/R even where tree establishment is technically feasible (IPCC, 2019; Nabuurs et al., 2022). Beyond biophysical suitability for establishment, site selection should assess the environmental controls on the magnitude and durability of carbon storage. Climate, soil properties, hydrology, nutrient availability, topography, rooting depth, and disturbance exposure influence growth rates, mortality, belowground carbon dynamics, and the relative contribution of different ecosystem carbon pools. These factors also interact: for example, water limitation can constrain growth even on otherwise fertile soils.

2.2. Ecosystem recovery potential and resilience

Beyond biophysical site suitability, the capacity of a site to recover toward forest conditions depends strongly on ecological legacies and landscape context. Past land-use intensity and duration influence residual vegetation, seed banks, resprouting capacity, soil properties, and competition from persistent grasses or other vegetation, while proximity and connectivity to remnant forests affect the supply of seeds and other propagules and the availability of animal dispersers (Holl, 2007). Sites with lower-intensity prior land use, remaining forest structure, and nearby propagule sources may therefore recover through natural or assisted natural regeneration, whereas isolated or heavily degraded sites may require more intensive interventions such as direct seeding or planting (Holl and Aide, 2011). Global synthesis further indicates that recovery rates and trajectories differ with previous land use, climate, and restoration approach, with some ecosystem functions recovering substantially more slowly following intensive agricultural use (Meli et al., 2017). These differences are directly relevant to A/R-as-CDR because they affect the rate of biomass accumulation, the time required to establish additional carbon storage, the level of management intervention required, and the likelihood that recovery persists without continued inputs.

2.3. Environmental risk assessment

Environmental risk assessment for A/R-as-CDR focuses on risks to carbon durability and ecological integrity: wildfire, drought, frost, pests/disease, invasive species, storms, floods, landslides and maladaptation (e.g., planting in water-limited landscapes). Environmental suitability and disturbance risk determine growth rates (the removal trajectory) and carbon storage permanence. Screening should incorporate both current and future climate conditions, including projected frequency and extent of extreme events (heatwaves, drought, storms), fire-weather risk, and pest/pathogen

pressures. This assessment is inherently difficult because future disturbance regimes mostly depart from historical experience, while the rare and compound events most consequential for carbon permanence are also among the hardest to characterize statistically and project at local scales. Increasingly, discussions around the integrity of forest-based carbon offset treat disturbances as central design constraints rather than downstream uncertainties, which means site selection must include forward-looking risk screening and not rely only on historical averages (Berry and Brown, 2021; Mummery, 2024). The IPCC emphasises that the mitigation potential of A/R is highly sensitive to climate drivers and assumptions, reinforcing the need for forward-looking suitability assessment rather than reliance on historical averages (Anderegg et al., 2020, 2022; Nabuurs et al., 2022). In parallel, surface properties, soil depth, soil texture, drainage, salinity, slope, and erosion susceptibility should be evaluated because they can affect establishment success and net GHG outcomes. For example, where slopes are steep or soils are fragile, site preparation and access can increase erosion risk and raise both costs and monitoring complexity.

2.4. Political feasibility

Even where biophysical conditions seem suitable for forest establishment and long-term carbon storage, an A/R intervention may remain politically infeasible, as A/R often competes with powerful interests (e.g., agriculture, ranching, mining, infrastructure). Because A/R-as-CDR typically requires multi-decadal continuity in land management, political feasibility hinges on whether influential actors—including ministries, local government and administration, producer associations, and customary authorities—perceive the A/R intervention as compatible with development priorities and whether policy commitments, such as land-use plans, or existing legally binding climate and restoration targets, are sufficiently stable to sustain commitments over time. Site selection should therefore include a political-economy assessment to identify likely veto points, instability risks, and competing land-use agendas that could undermine durability or additionality. Case-based governance research show that forest restoration succeeds more reliably where policy signals are stable, agencies have implementation capacity, finance persists beyond short project cycles, and local actors view the intervention as legitimate rather than externally imposed (IPCC, 2019; Mansourian et al., 2022).

2.5. Governance and legal compliance

Weak governance can hinder implementation by undermining land access, enforcement, maintenance, monitoring, and dispute resolution (Sendzimir et al., 2011; Ahammad et al., 2023). In particular, weak law enforcement, corruption, and limited accountability can increase risks of illegal harvesting, grazing encroachment, conflicts over land use, and other forms of degradation (Koyuncu and Yilmaz, 2009; Tacconi and Williams, 2020). Site selection, thus, examines government effectiveness, law enforcement capacity, and local dispute-resolution mechanisms, particularly where land-use pressures are high. More broadly, effective landscape governance also depends on the capacity of actors operating across sectors and scales to negotiate competing objectives, manage trade-offs, and sustain legitimate collective action (Van Oosten, 2021). Where contracts, land-use rules, or post-project exit provisions permit rapid reconversion, or where maintenance obligations are weakly enforced, CDR claims premised on durable carbon storage becomes fragile.

Legal compliance forms part of this assessment by determining whether

A/R establishment is permissible and compatible under relevant land-use zoning, protected-area rules, riparian buffers, planting restrictions, and permitting requirements. Carbon-focused projects also require clarity on who can legally claim, contract, and transfer carbon benefits and who bears liability in the event of reversal (Palmer, 2011; Streck, 2020). These questions are particularly important where land, tree, and carbon rights are held by different actors or where customary and statutory tenure overlap (Loft et al., 2015; Streck, 2020). Because land-based mitigation can create ecological and social trade-offs, many jurisdictions and standards increasingly impose stronger safeguards for biodiversity and ecosystem protection, including avoiding the conversion of high-nature-value ecosystems and alignment with biodiversity and ecosystem protection expectations (IPCC, 2019). Relevant tenure and rights safeguards can be assessed using frameworks such as the FAO Voluntary Guidelines on the Responsible Governance of Tenure (FAO, 2022).

Policy instruments and incentives, such as agricultural subsidies, restoration grants, and payments for ecosystem services can alter landholder incentives and shape A/R feasibility. Their implications for carbon accounting depend on the scale and purpose of assessment: at the project level, particularly in voluntary carbon markets, pre-existing incentives may complicate demonstrations of additionality, whereas at national or global scales such policies may themselves be part of the mitigation strategy. Conversely, conflicting incentives can pull land back toward agriculture or development. Where projects pursue carbon finance, eligibility and quantification depend on the selected MRV framework and carbon standard. For example, Verra VM0047 and the UK Woodland Carbon Code specify site-eligibility, accounting, and monitoring requirements that affect whether a project can generate credible claims (Verra, 2025; Woodland Carbon Code, 2025). These accounting requirements should be matched by an MRV design capable of measuring the required variables with sufficient accuracy, frequency, and institutional continuity over the project period.

2.6. Competitive land use and opportunity costs

Site selection for A/R confronts competition with other land uses, and this competition can constrain practical site availability, undermine long-term durability, and even drive carbon leakage and social opposition. Assessment should therefore extend beyond officially mapped land cover to include current, seasonal, and customary uses such as cropping, grazing, rotational fallows, fuelwood collection, foraging, and communal resource use or protective purposes. Displacing these activities can threaten food security and livelihoods, generate social opposition, and create leakage where production or resource extraction shifts elsewhere (Bao et al., 2026). Where such functions are important, degraded lands or multifunctional approaches such as agroforestry and silvopasture may reduce displacement while maintaining livelihood functions (Nabuurs et al., 2022; Brancalion and Holl, 2025).

Opportunity costs can also constitute a major component of A/R feasibility, shaping where projects are financially viable, what compensation or incentives are required for adoption, and whether land remains committed to forest use as commodity prices or land rents change (Li et al., 2026). Profit-driven alternatives, including commercial crops, pasture intensification, infrastructure, or energy development, should therefore be considered because higher or faster returns from competing uses can increase the incentives required for A/R and raise reversal risk if economic conditions change. Global analyses (e.g., Torres et al., 2010; Austin et al., 2020; Grafton et al., 2021) show that A/R feasibility differs sharply across regions because land value, opportu-

nity costs, and expected carbon accumulation vary in combination; sites with high opportunity costs can be financially unattractive even where growth rates are high.

2.7. Monetary and non-monetary benefits

Site selection should also include a realistic appraisal of expected revenue streams and associated uncertainties (Hildebrandt and Knoke, 2011). Potential monetary benefits include carbon credits, payment for ecosystem services, restoration subsidies, and, depending on management goals and safeguards, timber or non-timber products and services (Knoke et al., 2016, 2020). However, carbon revenues depend on methodology rules such as monitoring frequency, uncertainty deductions, buffer contributions, and verification schedules, which can materially affect project feasibility. For instance, ACR's *Afforestation and Reforestation of Degraded Lands* methodology specifies land-eligibility and carbon-accounting requirements that directly constrain which sites can qualify for crediting (American Carbon Registry, 2017); among other conditions, projects must be established on degraded land expected to remain degraded in the absence of the intervention, while wetlands are excluded and specific restrictions apply to organic soils and soil disturbance. Costs should be comprehensively budgeted, including planting stock, site preparation, labour, maintenance, protection, and the full suite of MRV and transaction costs (validation/verification, registry fees, due diligence). Underestimating these costs can undermine project viability, weaken long-term maintenance, and thereby increase non-permanence risk (Galik et al., 2012; Tedesco et al., 2022; Schuett, 2024). Non-monetary benefits including recreation, cultural values, biodiversity enhancement, watershed protection, erosion control, and social well-being, can likewise influence stakeholder support and overall project feasibility (Zheng et al., 2016; Griscom et al., 2017; Burton et al., 2018).

2.8. Tenure security

Tenure security is foundational for permanence, benefit-sharing, and dispute avoidance: unclear or contested rights often generate conflicts, inequitable benefit sharing, reversals, and delivery failure (Corbera et al., 2011; Legesse et al., 2018; Vincent et al., 2021; Rakotonarivo et al., 2023). Tenure security establishes who holds enforceable rights to land and trees, whether those rights persist across inheritance or sale, and whether carbon rights and liabilities are defined and contractable over the crediting or management period. Weak or contested tenure can therefore increase the risk of non-delivery, reversal, and non-permanence, consistent with broader evidence that tenure security is associated with improved forest persistence (Barbier and Tesfaw, 2013; Robinson et al., 2014; Benzeev et al., 2025). Using recognised governance benchmarks such as the FAO Voluntary Guidelines on the Responsible Governance of Tenure can provide a structured approach for assessing tenure risks and safeguards (FAO, 2022).

2.9. Inclusive decision-making

Because landscape-level A/R involves actors operating across different sectors and scales, inclusive decision-making requires not only stakeholder participation but also the institutional and collaborative capacity to negotiate competing objectives, trade-offs, and power asymmetries (Van Oosten et al., 2021). Inclusive decision-making recognises that A/R is implemented on inhabited landscapes where rights, livelihoods, and identities intersect. Inclusion affects participation rates during the implementation phase and subsequent monitoring, conflict risk, and ultimately net removals (Schirmer and Bull, 2014; Löfqvist et al., 2023; Schubert et al., 2024). Evidence suggests that par-

ticipation depends on whether project design aligns with landholder goals, preserves perceived autonomy, offers credible long-term returns, builds institutional trust, and avoids unacceptable changes to valued landscape functions such as grazing access, fuelwood collection, cultural sites, or other locally important uses (Schirmer and Bull, 2014). Accordingly, site selection should integrate social feasibility assessment. At the household level, landholder decisions often reflect age, labour availability, risk tolerance, access to capital, the perceived flexibility of land-use options, and personal motivations and beliefs (e.g., stewardship values versus production priorities; Perkins et al., 2023). Likewise, equity and ethics are not ancillary to inclusivity; they are determinants of legitimacy and permanence. Site selection also ought to include explicit safeguards for gender equity (e.g., ensuring women participate in decision forums and benefit-sharing), fair distribution of benefits and burdens, and rights-respecting engagement with Indigenous Peoples and local communities. Where relevant, free, prior, and informed consent (FPIC) should be treated as a prerequisite rather than a procedural checkbox (Stanturf et al., 2017; Fa et al., 2020; Dawson et al., 2021; IUFRO, 2021). Early stakeholder mapping, identifying landholders, tenants, common-rights users, local authorities, and downstream water users, helps prevent later conflict, renegotiation, or the withdrawal of landholders and other participants from agreed project commitments.

2.10. Forest-related infrastructure

Implementation feasibility also often depends on the availability of enabling infrastructure. Access roads influence logistics, fire response, and the practicality of repeated monitoring visits. In remote sites, road and track planning strongly affects cost, erosion risk, operational safety, and fossil-fuel emissions associated with implementation and repeated site access for maintenance and monitoring, which should be captured in the life-cycle assessment of project implementation. Screening should therefore consider whether access can be achieved without unacceptable ecological damage or prohibitive expense (Forestry Commission, 2011; Tran et al., 2019; Beguš and Pertlik, 2020). Irrigation access and infrastructure may influence seedling survival and overall establishment success in dry climates, particularly where supplemental watering is required during the early establishment phase. However, irrigation can increase pressure on groundwater or surface-water resources, while afforestation itself can reduce downstream water yield in many catchments, making hydrological impacts important for both ecological sustainability and social acceptance (Farley et al., 2005).

3. Species selection, establishment pathway, and planting-material readiness

Establishing A/R-as-CDR requires coupled decisions about how forest recovery should occur, what species and provenances are appropriate, where active introduction is required, and, whether suitable reproductive material and planting stock can be supplied at the necessary scale (Brancalion and Holl, 2020; Di Sacco et al., 2021; Holl and Brancalion, 2022). As previously discussed, these decisions are shaped by multiple interacting considerations, including site conditions, projected climate, establishment and growth characteristics, biogeophysical effects such as water use and albedo, biodiversity objectives, management requirements, stakeholder preferences, livelihood or cultural objectives, and potential revenues from timber and non-timber products (Jackson et al., 2005; Bonan, 2008; Brancalion and Holl, 2020; Di Sacco et al., 2021). Species should also not be considered in isolation: the composition and diversity of the

resulting forest and choices about species mixtures, functional and structural diversity, and interactions among species, can influence stand development, resilience, biodiversity, and longer-term carbon storage (Pretzsch et al., 2021; Warner et al., 2023). For active introduction pathways, species choice is constrained by whether appropriate reproductive material can be sourced and propagated at the quality, quantity, and timescale required for implementation (Allen et al., 2024); limitations in seed availability, provenance documentation, or nursery capacity can therefore make otherwise suitable species choices operationally infeasible (Broadhurst et al., 2008; Prober et al., 2015; Ladouceur et al., 2018; Fargione et al., 2021).

3.1. Establishment pathway

A/R does not necessarily require tree planting. Depending on site conditions, landscape context, propagule availability, prior land-use intensity, and restoration objectives, forest recovery may proceed through natural regeneration, assisted natural regeneration (ANR), direct seeding, planting, or combinations of these approaches (Holl and Aide, 2011; Holl and Brancalion, 2022). ANR builds on regeneration processes—for example, naturally established seedlings, saplings, or resprouts—by removing barriers such as competition, grazing, or recurrent fire and selectively protecting or releasing desirable regeneration. The species already regenerating on a site should therefore be assessed before deciding whether and what to plant, because established natural regeneration may provide a lower-input, less costly, and potentially faster route to forest recovery than replacing it with nursery stock (Holl and Aide, 2011; Chazdon et al., 2020). However, its feasibility as well as carbon and biodiversity outcomes vary substantially among locations (Crouzeilles et al., 2017; Lewis et al., 2019; Li et al., 2026). In this case, where propagule limitation, severe degradation, or compositional objectives constrain recovery, more active interventions may be required to establish some or all of the desired species.

3.2. Species availability and ecological suitability

Species selection is often described as an ecological matching exercise, but for A/R-as-CDR, it is more accurately understood as a feasibility intersection among project goals, current and future site conditions, nursery and seed constraints, expected costs and benefits, management requirements, stakeholder preferences (see Sect. 3.3), compatibility with other land-use objectives as well as downstream processing and market infrastructure. Compatibility, therefore, extends beyond 'will this species grow here now?' to 'can this species–provenance combination plausibly persist and store carbon here over the project's permanence horizon?' while generating acceptable costs and benefits and avoiding unacceptable trade-offs with other land-use goals.

Climate adaptation guidance increasingly recommends explicit attention to provenance choice and to within-species variation, because climate change can render traditional seed sourcing practices maladaptive, particularly for long-lived perennials with long rotation or restoration lifetimes (Bower et al., 2024; Stanturf et al., 2024). Current and expected future temperature, precipitation, soils, hydrology, and disturbance regimes determine whether a species can establish and grow successfully, while provenance and seedlot choice can further influence establishment, growth, and resilience through within-species genetic variation (Forest Research; Forestry Commission, 2020; Prober et al., 2015).

Early growth and rapid canopy development are relevant, because rapid es-

tablishment and canopy development can suppress competing vegetation, reduce establishment-phase management requirements, and accelerate initial carbon accumulation. These advantages should, however, be balanced against longer-term growth, longevity, diversity, and resilience rather than treating rapid early growth as an objective in itself. Climate-informed sourcing approaches therefore increasingly consider provenances expected to perform under both current and projected conditions, including climate-adjusted seed transfer and, in some cases, assisted migration, increasingly supported by decision tools that integrate site and projected climate information (Fremout et al., 2022; Palik et al., 2022; Vitt et al., 2022; Adams et al., 2024; Wotherspoon et al., 2025). Such strategies can reduce future maladaptation risk but introduce uncertainty associated with climate projections, near-term establishment conditions, and biotic interactions; decision-support tools can help operationalise these choices where suitable data and governance for seed movement are available (Silva et al., 2025).

3.3. Socioeconomic considerations in species selection

Species selection is not solely a technical exercise because candidate species and planting designs differ substantially in the benefits, costs, management demands, and functions they provide to affected stakeholders. Landholders typically prioritise attributes such as income potential, timber or non-timber products, management requirements, rotation length, or flexibility to retain other land uses, whereas local communities may place greater emphasis on access, cultural values, landscape aesthetics, biodiversity, or other locally valued ecosystem functions (Nijnik and Mather, 2008). These preferences vary among households and social groups according to livelihood strategies, labour availability, capacity to absorb delayed returns, and the resources or products obtained from particular tree species (Schirmer and Bull, 2014; Sutherland et al., 2021). Consequently, a species or mixture that is biophysically well suited to a site may still perform poorly as an intervention if its expected uses, management requirements, or consequences for existing landscape functions are unacceptable to those responsible for maintaining it (Schirmer and Bull, 2014). Beyond individual landholder decisions, community-level acceptance can also influence which species and planting designs are likely to be maintained over time. An inclusive species-selection process should therefore identify the objectives and preferences of relevant stakeholders early and use these alongside ecological and operational criteria. It should also ensure that all relevant stakeholder groups can contribute to species-selection decisions (Chhem et al., 2025). This may involve discussing expected products and benefits, management obligations, time to returns, compatibility with existing land uses, and perceived ecological or cultural trade-offs. Stakeholder engagement can also reveal locally important constraints or species attributes that may not be captured in technical suitability assessments, while transparent discussion of trade-offs can reduce the risk that planting designs are perceived as externally imposed (Ambrose-Oji et al., 2018; Staddon et al., 2021). The objective is to identify ecologically suitable options that are compatible with stakeholder priorities and therefore more likely to be accepted, maintained, and sustained over the intended carbon-storage period.

3.4. Seed banks and seed systems as restoration infrastructure

Seed banks and broader seed production systems are critical restoration infrastructure because they determine whether A/R can be implemented with adequate genetic diversity and provenance integrity. Seed availability is increasingly recognised as a practical bottleneck in restoration, especially for diverse native-species mixtures,

because supply chains often cannot provide sufficient volume, provenance documentation, or genetic diversity at the time and scale required (Ladouceur et al., 2018; Allen et al., 2024). When supply is limited, projects may default to a narrow set of commercial species or uncertain-provenance material, raising climate vulnerability and undermining ecological objectives. Scaling restoration, therefore, requires not just collection but storage, viability testing, bulking, traceability, and documentation, functions commonly supported by ex situ seed banks and associated networks (Ladouceur et al., 2018; Wambugu et al., 2023). Recent guidance stresses that 'getting seed right' includes maintaining genetic integrity across collection, processing, storage, and deployment, and capturing genetic diversity representative of target populations while aligning seed transfer decisions with restoration goals and environmental gradients (Pedrini et al., 2020b). Seed sourcing often involves permitting and stewardship constraints, particularly in protected areas or where wild populations are vulnerable, meaning that seed availability and governance should be assessed early in site selection and project design rather than only during implementation (National Academies of Sciences, 2023). Practically, site screening should assess whether seed systems can provide the right species, with documented provenance and genetic representativeness, in quantities and timelines that match planting schemes, and should track the full seed pathway from source populations and permits through storage/viability testing, nursery propagation, and outplanting records to avoid maladaptation and genetic bottlenecks and to support credible claims (Vander Mijnsbrugge et al., 2010; Wambugu et al., 2023).

3.5. Tree nursery capacity and quality assurance

Tree nurseries are a core enabling component of A/R planting projects. Nursery constraints often emerge during site selection as constraints on timing of sufficient production for planting design strategies and quantity of physiologically and genetically suited seedlings necessary for the project area (Fargione et al., 2021). Standard nursery guidance emphasises that production planning must align species requirements, propagation methods, and anticipated outplanting schedules, while accounting for water availability, labour, infrastructure, and hardening regimes that improve seedling survival following planting (Aldhous and Mason, 1994; Longman, 1998). Seedling establishment success is strongly sensitive to seedling physiological condition and root development, handling, and hardening, so 'hectares planted' is usually a weak proxy for CDR performance unless stock quality is controlled (Jaenicke, 1999; Mataruga et al., 2023). These issues are consequential for CDR-oriented A/R because establishment failure is not only a silvicultural concern but a carbon accounting risk that can propagate through permanence and delivery claims.

The nursery stage must also consider phytosanitary and biosecurity risks: nursery operations typically require traceability, hygiene protocols, and quality assurance standards to reduce the risk of transferring pathogens and pests from production to restoration sites (Morgan, 1999), which can further limit production. These constraints imply that biophysically suitable sites may still be operationally infeasible if nursery supply chains cannot provide the required volume of healthy stock without elevating biosecurity risk. Operationally, screening should consider (i) proximity and accessibility of nurseries (which affects transport stress and planting windows), (ii) production system type (containerised vs. bare-root), (iii) evidence of routine quality monitoring (morphological and physiological traits, survival tracking), and (iv) disease and pest management protocols. While reviewing practices across Europe, Mataruga et al. (2023) also emphasised that seedling quality definitions and monitoring regimes

vary substantially by country and planting context, which has direct implications for comparability and MRV confidence across projects. Where institutional capacity is limited, nursery planning guidance and standard operating procedures become part of feasibility, not a downstream detail (Aldhous and Mason, 1994; Carsan and Munjuga, 2020).

4. Field implementation and early management

Field implementation translates the selected pathway into on-the-ground action, acting as the operational bridge between 'site selected' and 'forest established'. It determines whether the chosen site and species enter a sustained trajectory of survival and carbon accumulation in the A/R process chain. Site preparation and early implementation should therefore be matched to the selected regeneration pathway and the barriers to establishment. The form and intensity of site preparation depend strongly on whether recovery proceeds through natural regeneration, assisted natural regeneration, direct seeding, planting, or a combination of these approaches. Where natural regeneration potential is high, little physical site preparation may be required, and intervention can focus instead on removing barriers to recovery (Crouzeilles et al., 2017; Holl and Aide, 2011). Depending on the site conditions, this may involve (i) facilitating natural or assisted regeneration or implementing direct seeding or planting; (ii) site modification and protection, including ground preparation, guarding, and browsing control; and (iii) early competition management, such as mulching or weeding, implemented by a workforce with appropriate skills and protections. For pathways requiring active establishment, site preparation can determine whether seed or planting stock survives the critical early years when mortality is often highest and establishment failures can lead to costly reseeding or replanting and reduced carbon accumulation. Preparation may aim to create favourable microsites through improved soil contact, moisture, and temperature conditions, reduce early competition, and limit disturbance-related mortality. Reviews in temperate and boreal systems generally find that scarification, mounding, or ripping can improve early survival and growth by improving microsite conditions and reducing competition, although effects depend strongly on soil moisture, fertility, and disturbance intensity (Löf et al., 2012; Sikström et al., 2020). These interventions also create trade-offs: intensive soil disturbance can increase erosion risk, alter understory biodiversity, and sometimes provide only short-lived control of competing vegetation (Löf et al., 2012).

The remainder of this section focuses primarily on the operational requirements of active establishment through direct seeding and planting, together with early protection and vegetation management, while longer-term interventions following establishment are addressed in Section 5.

4.1. Workforce (expertise, availability, labour protection)

Workforce capacity matters for carbon delivery because establishment quality and early survival depend heavily on whether sufficient skilled labour and appropriate technical expertise are available at the right time. This includes the workers for site preparation and planting, as well as specialist skills required for activities such as species identification, seed collection, nursery management, and monitoring. Site preparation can be labour-intensive and safety-critical. Workforce considerations are therefore not an implementation afterthought but a feasibility determinant of whether

establishment operations can be executed at the required pace and quality. Studies comparing manual and mechanized operations (e.g., Khoza et al., 2024; Kemppainen et al., 2025) highlight large productivity differences linked to operator experience and worksite conditions, implying that training and deployment planning are central to feasibility. Expertise and training can also influence planting quality (root placement, depth, firming, handling), correct installation of guards/fences, safe machinery operation, and appropriate herbicide use where applied. National competency standards reflect the breadth of tasks involved in managing planting and establishment operations, including ground preparation, method choice, and supervision (Lantra, 2024). The availability and seasonality of the workforce also matter because planting windows are narrow; shortages can force rushed planting, longer transport or storage times for stock, and associated quality losses. Labour protection is equally important because forestry work (including planting) involves risks from tools, machinery, weather exposure, difficult terrain, and chemical handling. The ILO's (International Labor Organization) code of practice provides a foundational reference for safety management, risk assessment, training, Personal Protective Equipment, and protection for workers and bystanders at or near forestry worksites (FAO et al., 2023; ILO, 2025).

4.2. Sowing

Direct sowing of seeds at a site can reduce nursery and transport requirements, reduce pathogen transfer, and, in some contexts, enable rapid treatment of large or inaccessible areas, but success is highly contingent on seed quality and supply, microsite suitability, predation pressure, and moisture conditions. Because germination and early establishment rates are often low, direct seeding may require large quantities of viable seed, making seed availability, cost, provenance, and collection capacity important practical constraints, particularly for diverse native-species mixtures (Ladouceur et al., 2018; de Souza and Engel, 2023; Ferreira and Vieira, 2024). Sowing rates may therefore exceed desired final stocking, although higher seed densities cannot compensate for unsuitable microsites or other establishment limitations. Establishment guidance emphasises careful attention to site preparation, sowing time, seed pre-treatment (e.g., scarification, stratification), and post-sowing protection to mitigate losses from desiccation and predation (Chapman and Allan, 1978). A field-performance review by Grossnickle and Ivetić (2017) show that direct seeding is less predictable than planting because emergence and survival depend heavily on seed handling, seed–soil contact, predation pressure, and post-seeding moisture conditions. Where establishment is adequate, direct seeding can nevertheless reduce nursery and planting costs relative to planting nursery-raised stock, although high seed requirements, seed processing, variable emergence, and repeat interventions can erode this advantage (Raupp et al., 2020; Ferreira and Vieira, 2024).

Direct seeding approaches include hand broadcasting or spot/line sowing, mechanised line or drill seeding, and aerial or UAV-based dispersal. Hand sowing can be labour-intensive and difficult to scale over large areas, but offers considerable flexibility, particularly in heterogeneous terrain where workers can target favourable microsites and adjust seed placement to local soil, moisture, vegetation, and topographic conditions. Sowing depth and seed–soil contact may, however, be less consistent than with mechanised approaches, making adequate placement and coverage important for germination and early root development (Chapman and Allan, 1978). Mechanised seeding can improve consistency of seed placement and increase throughput where terrain, access, equipment, and ground conditions permit. Aerial or UAV-based seeding can rapidly treat large or inaccessible areas, but provides less control over seed

placement and seed–soil contact, while establishment may remain constrained by predation, herbivory, moisture stress, and limited seed incorporation (Stamatopoulos et al., 2024). Early growth and stocking may also lag natural regeneration depending on site constraints and seed availability (Xiao et al., 2015). Method choice therefore involves trade-offs among spatial precision, throughput, seed-use efficiency, labour and equipment requirements, accessibility, and establishment risk, and should be matched to site conditions rather than throughput alone.

4.3. Planting (Nursery-raised stock)

Planting nursery-raised seedlings or saplings is widely used where greater predictability and control over initial stocking, species composition, provenance, and establishment are required. Relative to direct seeding, planting reduces some early-stage uncertainty and can provide tighter control over species mixtures and provenance documentation, particularly where carbon-accounting or compliance frameworks require traceability of planting material. Planting need not involve uniform, full-area establishment; depending on regeneration potential and project objectives, it may range from intensive planting across the site to enrichment, cluster, or gap planting that supplements natural regeneration. Once planting is selected, establishment success depends on both planting technique and the microsite conditions (Wallertz et al., 2018; Sikström et al., 2020), which can often be improved by mechanical site preparation. Hand planting can accommodate heterogeneous terrain and allows planters to adjust planting depth, root placement, and firming to local conditions. Appropriate handling, avoidance of root desiccation, and good soil contact are important for early survival (Johansson, 1993; The Tree Council, 2019). Mechanised planting can increase throughput and reduce dependence on manual labour, but its feasibility is constrained by equipment availability and terrain characteristics such as slope, surface roughness, soil conditions, and ground obstacles. It can also reduce unit labour costs where terrain and equipment availability permit, although savings may be offset by mobilisation costs or by establishment failures requiring replanting (Khoza et al., 2024). Productivity and planting quality also depend on machine type and operator skill, so mechanisation can introduce additional quality-control requirements even where it improves operational efficiency (Khoza et al., 2024; Kemppainen et al., 2025).

Planting density controls early canopy closure (affecting weed pressure and microclimate), thinning needs, habitat structure, and costs. Higher densities increase upfront costs (plants + labour + protection) but can provide resilience against early mortality and enable later selection thinning. Optimal spacing is therefore tightly coupled to site productivity and weed dynamics. Age and size of planting stock involve trade-offs among unit cost, handling requirements, competitive ability, and establishment performance. Larger stock may establish more quickly, have higher survival (Andivia et al., 2021) and compete better with surrounding vegetation, but is generally more expensive to produce, transport, and plant. Transplant shock and post-planting water and heat stress can affect stock of any size and depend strongly on physiological condition, root-system integrity, hardening, planting quality, and the match between stock type and site moisture conditions (Mataruga et al., 2023; Puértolas et al., 2024). The relevant question is therefore not simply whether larger stocks survive better, but whether any survival or growth advantage justifies its greater production, transport, and planting costs under the conditions of the target site.

4.4. Timing of establishment

Timing is critical for both direct seeding and planting, but the relevant constraints differ between the two approaches. For direct seeding, germination and early root development are tightly coupled to soil moisture and temperature, so sowing is commonly targeted to periods of predictable moisture availability, such as the onset of the wet season in seasonal tropics or suitable spring/autumn windows in temperate systems; under variable climates, timing can be as important as seed treatment or sowing method (Chapman and Allan, 1978; Grossnickle and Ivetić, 2017). For planting, timing should likewise minimise post-planting water stress as well as frost risk and may also be constrained by dormancy requirements in temperate regions. Planting outside favourable windows can increase mortality and the need for irrigation or replanting, while interactions with competition, shading, or nurse vegetation can further influence survival in dry or seasonal environments (Rey Benayas et al., 2005; Konaté et al., 2025; The Tree Council, 2019, 2025).

4.5. Initial establishment protection

Protection requirements vary with the establishment pathway, developmental stage and site conditions. For direct seeding, the main risks include seed predation by rodents or birds, desiccation, and displacement by runoff or erosion. Protective measures can include seed coatings or pelleting, placement in prepared microsites such as shallow pits, and temporary physical barriers (Grossnickle and Ivetić, 2017; Griffiths et al., 2025). Seed enhancement technologies can also improve handling and delivery and incorporate materials intended to reduce moisture stress, deter predators, or protect against pathogens, although their effectiveness is strongly species- and context-dependent (Gornish et al., 2019; Pedrini et al., 2020a; Brown et al., 2021; Stapleton et al., 2024; Ren et al., 2026).

Once seedlings are established, whether through planting or natural recruitment, herbivory can become a major source of mortality and growth suppression, including browsing, bark stripping, and fraying, particularly where deer or other large herbivore densities are high. Tree shelters and individual guards can reduce such damage and may improve early height growth where herbivore pressure is high, although their benefits are more limited where other stresses dominate (Abe, 2022; Oliet et al., 2023). Because individual protection can be difficult to scale owing to material, installation, and maintenance costs, fencing or population-level herbivore management, including regulated hunting or culling where legally and socially appropriate, may be more practical in some settings (The Tree Council, 2019; Harries, 2025).

4.6. Herbivory control (hunting, sapling protection)

Vertebrate herbivory is a major cause of regeneration failure and can shift species composition (e.g., favouring less palatable species) with long-run impacts on carbon trajectories. A synthesis of deer-browse mitigation found that fencing and shelters can reduce damage, but the most effective option depends on herbivore density, landscape openness, maintenance capacity, and whether the goal is short-term seedling protection or long-term browsing reduction (Redick and Jacobs, 2020). Findings from restoration under arid and semi-arid stress also suggest that protection structures can meaningfully alter survival outcomes, though results depend on design and site conditions (Abe, 2022; Oliet et al., 2023). Where livestock pressure exists, evidence indicates consistently negative impacts on tree regeneration in some systems (e.g., oaks), affirming fencing/grazing management as a permanence-relevant maintenance

action (Wadud et al., 2024).

4.7. Irrigation

Irrigation is often used as a targeted establishment and drought-buffering tool rather than a long-term silvicultural norm, although in some arid and semi-arid afforestation projects supplemental watering may be required beyond the initial establishment phase where natural water availability is insufficient to sustain stand development. Field experiments in Mediterranean restoration contexts by Siles et al. (2010) show that supplemental watering can improve seedling survival under strong seasonal drought, although responses differ across species and the gains may not justify the cost where watering cannot be sustained. Other studies in post-fire or high-stress environments (e.g., Padrón et al., 2020) similarly report benefits of summer irrigation and mulching for reducing transplant water stress, though costs and feasibility can limit scaling. For maintenance planning in managed forest stands, long-term irrigation experiments also show that sustained water addition can change canopy structure and growth metrics, implying that irrigation can alter stand development pathways, not just short-term survival (Bose et al., 2022). Irrigation therefore affects not only immediate establishment success, but also whether later stand development remains feasible under water-limited conditions without creating new hydrological trade-offs.

4.8. Liming

Liming is applied to counteract soil acidification, modify nutrient availability, and sometimes improve growth in acid-sensitive systems. Liming decisions influence carbon outcomes by altering both soil chemistry and the mix of soil organic carbon (SOC) versus inorganic carbon that MRV must ultimately track. Its carbon implications therefore also intersect with enhanced weathering and soil inorganic carbon pathways. In conventional forest management, however, liming is primarily a soil amendment rather than a CDR intervention. This distinction becomes clear where alkaline mineral additions promote bicarbonate formation or inorganic carbon storage, creating a conceptual overlap with enhanced weathering. In European forests, liming has been associated with reduced forest-floor organic matter accumulation, while effects in mineral soils are more variable (van Straaten et al., 2023); long-term evidence also show that liming and fertilisation can alter the distribution of carbon among soil aggregates (Mosquera-Losada et al., 2015). These effects are relevant for MRV because soil organic carbon and soil inorganic carbon differ in formation, persistence, and accounting (Knapp and Tipper, 2022; Clarkson et al., 2024; Manning et al., 2024). By contrast, alkaline or silicate mineral additions can overlap conceptually with enhanced weathering where they promote bicarbonate formation, inorganic carbon storage, or SOC stabilisation; the net CDR value of such approaches would depend on the geochemical pathway, transport, and remobilisation (Knapp and Tipper, 2022; Buss et al., 2024; Clarkson et al., 2024; Xu et al., 2024).

4.9. Fertilization

Fertilization is most relevant where nutrient limitation constrains establishment or subsequent production. Fertilization can increase growth and accelerate canopy closure, while also increasing N_2O emissions, meaning apparent gains in biomass carbon may overstate net climate benefit if associated non-CO_2 emissions are not included in MRV (Rabbai et al., 2024). Because N_2O responses to nitrogen inputs are often nonlinear and can rise disproportionately at higher application rates, maintenance

plans that include fertilization should define conservative dosing, timing, and (where feasible) mitigation measures (e.g., improved N-use efficiency strategies; Shcherbak et al., 2014). In forest systems, fertilization can also interact with soil moisture and microbial processes, further complicating net climate outcomes (Aronson and Allison, 2012). Fertilization decisions therefore affect not only later biomass accumulation, but also whether apparent growth gains translate into defensible net removals once non-CO_2 emissions are included.

4.10. Mulching

Mulching is commonly used for weed suppression and to modify soil moisture and temperature conditions during establishment, but its hydrological effects are strongly context-dependent (Martin et al., 2025). Mulches can reduce soil moisture loss and suppress weeds, and impermeable barriers may also warm soils and support root growth, although these options can be costlier than chemical methods and require careful installation to avoid failures (e.g., gaps enabling weed ingress; Sellers, 2014). Field experiments in dry and Mediterranean-type environments show that appropriately applied mulching can improve early survival and growth in some settings, although responses vary with mulch type and depth, rainfall regime, drainage, and maintenance quality (Chaar et al., 2008; Martínez-Herrera et al., 2023; Oliet et al., 2023). The UK Forestry Commission guidance, however, cautions that on poorly drained sites, certain mulching approaches can exacerbate anaerobic soil conditions and harm young trees, reinforcing the need to match mulching prescriptions to soil drainage and site hydrology (Davies, 1987). Operationally, mulching decisions at site preparation usually specify: (i) mulch type (organic chips/straw vs. mats/fabric vs. plastic), (ii) application geometry (spot mulches around stems vs. strip mulches vs. full-surface treatment), (iii) maintenance requirements (re-application, pinning mats, repair after wind/animal disturbance), and (iv) cost thresholds, since mulching can shift costs forward but potentially reduce multi-year weeding burdens.

4.11. Weeding and early vegetation management

Control of competing ruderal vegetation, invasive non-natives, and/or pioneer species is often important for establishment and growth because they compete for light, water, and nutrients. In woodland establishment guidance, sustained vegetation control during the vulnerable first few years, through mowing, hoeing, herbicides where permitted, mulch, or other targeted treatments, is repeatedly emphasised as important for survival and early growth, particularly in grass-dominated sites or where seedlings are vulnerable to overtopping or drought stress (Williamson, 1992; Woodland Trust; Rey Benayas et al., 2005; Stokes and Willoughby, 2014). However, early-successional vegetation can either suppress seedlings through competition or temporarily protect them by moderating heat and moisture stress, so the net effect depends on abundance and structure of competing vegetation, drought stress, and species shade tolerance (Arias et al., 2021). Vegetation management should therefore be treated as an adaptive, potentially multi-year intervention: initial control may be required to secure establishment, followed by further treatments where renewed competition threatens survival or growth.

Weeding approaches span mechanical (mowing, hoeing), chemical, and physical suppression (mulch, mats). Studies on long-term regeneration and establishment indicate that vegetation control and ground preparation often improve seedling survival probabilities, particularly in the critical first growing season (Kerr et al.,

2008; Sikström et al., 2020). From a site-preparation perspective, the design problem is to set a control strategy that is feasible and cost-effective: (i) Method selection (manual/mechanical vs. mulching vs. herbicides where permitted) must align with site sensitivity (e.g., watercourses), legal restrictions, and workforce competence. (ii) Spatial targeting (spot/strip vs. area-wide) can reduce costs while protecting seedlings during the most vulnerable stage. (iii) Scheduling should anticipate peak competition periods and prioritise intervention before competition causes persistent growth suppression, thereby reducing subsequent maintenance and replanting needs.

5. Forest maintenance

Forest maintenance is the bridge between establishment and durable CDR. In A/R systems, maintenance determines (i) whether trees survive the high-mortality early years, (ii) whether stands remain resilient under climate extremes and biotic disturbances, and (iii) how carbon is partitioned among live biomass, deadwood, litter, and soils. Where competition persists beyond establishment, maintenance may include continued vegetation management as discussed earlier. More broadly, because most CDR crediting frameworks implicitly assume sustained stand function, maintenance actions should be framed as risk management for permanence as much as productivity management. Many maintenance actions matter for CDR not only because they maximize growth in the short term, but because they reduce the probability that previously stored carbon will later be lost. These actions therefore influence whether carbon gained after establishment is stabilized, redirected, or lost, and consequently the durability assumptions embedded in subsequent accounting and verification. In planted forests, thinning is a common stand-tending intervention where control of density, growth, or timber production is required, whereas pruning is generally more selective because of its cost and is typically concentrated on crop trees intended for higher-value timber; fertilization is likewise applied only where site fertility and management objectives justify it (FAO, 2020).

5.1. Assisted natural regeneration (including a change in species composition)

Following establishment, selective release, enrichment planting, or underplanting can be used to steer stand composition, diversity, productivity, or resilience where existing regeneration does not fully meet project objectives. ANR includes interventions that accelerate or redirect successional trajectories to improve survival, productivity, and resilience, often through enrichment planting, or selective release of naturally regenerating seedlings or saplings from competing vegetation, together with measures such as fire control, grazing exclusion, or other protection where recurrent disturbance constrains regeneration. ANR is often considered more cost-effective than full planting where seed sources, resprouting capacity, and local protection measures already exist, because the intervention can focus on releasing and protecting regeneration rather than establishing every tree from scratch (Chazdon et al., 2020; Oluwajuwon et al., 2024). Where project goals require higher-value timber, higher diversity, or climate/pest resilience, changing species composition via enrichment planting can steer future forest structure. For example, enrichment planting in tropical fragments has been shown to influence regeneration pathways and has well-characterized cost and implementation implications (Mangueira et al., 2019; Sugiyama et al., 2024). A resilience-driven composition shift (e.g., increasing functional diversity, mixing species

with different drought tolerance) can also reduce future vulnerability to pests and climate stress (Williams et al., 2024). These interventions therefore shape whether young stands develop into more resilient, carbon-accumulating systems or remain vulnerable to later mortality and underperformance.

5.2. Pest and disease management (biological, chemical)

Here, pest and disease management refers primarily to damaging invertebrates, such as defoliating insects, borers, and their larvae, and to pathogens such as fungi, bacteria, and viruses. Forest pest and disease management is largely responsive/risk-based, rather than necessarily scheduled treatment. It is increasingly framed through integrated pest management (IPM), combining monitoring, thresholds, silvicultural prevention, biological control, and targeted chemical use when necessary (Sweeney et al., 2023). For plantations, pest pressure can materially reduce growth and survival, creating direct carbon losses. Recent regional reviews emphasize that increasing complexity (e.g., mixed-species plantations) can improve pest resilience, though outcomes depend on pest ecology and landscape context (Villacide and Fuentealba, 2025). Biological control can, in principle, protect sequestration by preventing severe defoliation or mortality (Wyckhuys et al., 2025). However, both biological and chemical control methods should address non-target risks and ecosystem side effects. Pesticides can have substantial indirect impacts mediated through food-web effects and non-target mortality, underscoring the need for IPM and careful chemical selection (Sánchez-Bayo, 2021; Li et al., 2025).

5.3. Fire and fuel management

Fire/fuel management relevance is strongly hazard-dependent, but potentially critical throughout the project lifetime in fire-prone landscapes. Wildfire represents a major threat to the permanence of A/R projects because severe events can cause substantial tree mortality and rapidly reverse accumulated carbon storage. Fire prevention and suppression can reduce immediate fire risk; however, in some fire-adapted systems, prolonged exclusion of low-intensity fires can allow combustible fuels such as litter, dead wood, and dense understory vegetation to accumulate, potentially increasing the severity of subsequent wildfires (Anderegg et al., 2020, 2022; Jäger et al., 2024). Fuel-management measures, including thinning, prescribed burning, or targeted removal of understory and woody fuels, can reduce this hazard. Such treatments could involve a short- versus long-term carbon trade-off (Campbell et al., 2012; Restaino and Peterson, 2013). Because wildfire can have lasting effects on soils and detrital carbon pools, maintenance planning should explicitly integrate post-fire carbon dynamics and recovery pathways, including soil carbon responses, pyrogenic carbon formation, and erosion risk (Cheng et al., 2023; Zhou et al., 2025). For A/R-as-CDR, fire suppression should be part of a broader fire-risk strategy that includes fuel management, defensible space, and the restoration of more fire-resilient stand structures. Because many wildfire ignitions are human-caused, fire-risk assessment should also consider patterns of forest access and use, including proximity to roads, settlements, recreational areas, and other locations where human activity may increase ignition probability (Gelabert et al., 2025). Operationally, this means pairing fire suppression with a site-specific wildfire risk assessment and management plan that identifies ignition and spread hazards, prioritizes protection zones, specifies fuel-management measures such as strategic breaks and, where appropriate, thinning or pruning, plans access and water points for response, and sets out post-fire recovery actions where severe fire may affect soils, erosion, and regeneration (Hurteau, 2017; Meyer et al., 2021; Forestry Commission,

2014). The practical challenge is that long-term fuel management, monitoring, and response capacity may be costly and institutionally difficult to maintain, especially across large or remote project areas.

5.4. Pruning

Pruning is not a routine requirement across A/R projects, but a selective intervention most relevant to production-oriented stands where timber quality, tree form, or fuel-management objectives justify its additional cost (FAO, 2020). Pruning is employed to improve stem form and wood quality, manage crown architecture, and sometimes reduce ladder fuels. However, pruning removes photosynthetic areas and can temporarily reduce growth if too intensive or mistimed. In plantations, pruning can alter understory light and microclimate, with downstream effects on soil processes and understory competition, potentially also influencing carbon stocks indirectly, not only via tree growth (Huang et al., 2023). From a carbon perspective the key is that pruning effects are typically smaller than thinning effects on stand-level biomass, and are highly dependent on intensity and site productivity (Ali et al., 2025). In maintenance plans, pruning is best justified primarily through quality, health, and risk objectives, with carbon treated as a secondary (and context-dependent) outcome. Pruning therefore indirectly affects later carbon outcomes by altering stand structure, fuel continuity, and wood-quality pathways rather than by maximizing stored carbon on its own.

5.5. Thinning and partial harvesting

Beyond downstream product pathways, harvest intensity and retention pattern also determine the carbon impact. Partial harvesting reduces standing aboveground biomass carbon in the short term, while subsequent outcomes depend on regrowth, forest type, disturbance regime, and the intensity and spatial pattern of biomass removal (Zhou et al., 2013; Collin et al., 2025). Broader syntheses do not support a general assumption that thinning increases net carbon storage relative to no thinning, with outcomes varying substantially among forest systems and management regimes (Kalies et al., 2016; Zhang et al., 2024). Soil carbon responses to harvesting are especially important for CDR accounting. Johnson and Curtis (2001) found variable harvest effects on soil carbon and nitrogen that depend on harvest type and forest type. In a global study, James and Harrison (2016) reported an average reduction in forest SOC following harvesting, with stronger effects in forest floors than mineral horizons. For clearcutting in northern systems, evidence indicates potentially long-lasting reductions in forest-floor SOC, reinforcing that clearcut-based systems can carry longer soil-carbon recovery horizons (Johannesson et al., 2025). In tropical systems, post-logging regrowth can recover part of the carbon loss over time, but recovery depends strongly on logging intensity, collateral damage, soils, and climate, so regrowth should not be assumed to neutralize harvest emissions (Martin et al., 2015; Piponiot et al., 2016). For CDR claims, harvest regimes must therefore be aligned with the intended storage duration and product pathways (including the fate of harvested wood product (HWP) and potential substitution), as well as the MRV boundary and accounting approach, rather than treated as 'business as usual' silviculture (Rüter et al., 2019; Kayo et al., 2021; Haya et al., 2023). Where harvest-related removals are credited, accounting assumptions concerning baselines, leakage, reversals, and the fate of the HWP can materially affect the estimated mitigation outcome (Haya et al., 2023).

6. Carbon Storage and product removal

Carbon storage in A/R-as-CDR systems spans in-forest and out-of-forest pools that differ substantially in turnover time, vulnerability to reversal, and measurability. Assessing net CDR therefore requires more than measuring tree growth. The relevant quantity is the net change in carbon storage attributable to the A/R intervention relative to a credible counterfactual, assessed across the applicable accounting boundary and time horizon and including the fate of exported biomass and relevant management and life-cycle emissions. The CDR value of A/R therefore depends on gross tree growth as well as changes across carbon pools and transfers, together with disturbances and emissions associated with management and downstream product pathways. Conceptual clarity matters because commonly used terms such as sequestration can refer to different quantities (e.g., net primary productivity (NPP), net ecosystem productivity (NEP), or net biome production (NBP)), potentially leading to inconsistent claims where accounting boundaries are not explicit (Chapin et al., 2006).

6.1. In-forest storage

In-forest storage dynamics determine how much carbon is accumulated, as well as how vulnerable that carbon remains to redistribution and later release. Atmospheric CO_2 taken up by trees is allocated among stems, branches, foliage, and roots, while litterfall, root turnover, mortality, and decomposition progressively transfer carbon into deadwood, litter, and soils. These pools differ markedly in size, turnover time, and sensitivity to management and disturbance, so an increase in one pool does not necessarily imply an equivalent increase in total ecosystem carbon storage. The balance among these pools also changes as stands develop. Young forests may accumulate carbon rapidly in living biomass, whereas increasing stand age can shift a larger fraction of carbon through dead organic matter and soil pathways. Management interventions such as thinning or harvesting, or other disturbances, can further redistribute carbon among carbon pools. The durability of in-forest storage is likewise heterogeneous. Carbon retained in long-lived woody biomass or relatively persistent soil fractions may remain stored for decades or longer, while foliage, fine roots, litter, and some dead organic matter turn over much more rapidly. For CDR assessment, the important question is therefore how carbon moves through the forest system and how much remains stored across the chosen accounting horizon.

6.1.1. Carbon uptake and carbon sequestration

Forests remove CO_2 from the atmosphere through photosynthesis (gross primary production; GPP), storing part of that carbon as biomass while returning part to the atmosphere via autotrophic and heterotrophic respiration. What ultimately matters for CDR is the net balance, often expressed as NEP (Chapin et al., 2006) and, when disturbances and lateral transfers are included, NBP. At a global scale, inventory-based analysis indicates that the world's forests were a large net carbon sink over recent decades, though with substantial spatial variation and sensitivity to disturbance and land-use change (Pan et al., 2011, 2024). A key implication for A/R-as-CDR is that sequestration is a trajectory, not a one-time outcome: young stands typically accumulate carbon rapidly in biomass, while older stands may continue accumulating carbon (including in soils) depending on disturbance regimes, management and environmental changes (Luyssaert et al., 2008, 2021). It remains unresolved whether all carbon sequestration on an A/R area is attributable to CDR, even if it is driven not directly by the land-use practice of A/R itself, but occurs in response to environmental changes (such as increasing atmospheric CO_2). Additionality to natural processes

is typically seen as part of the definition of CDR (Geden et al., 2024; Swoboda and Oschlies, 2025), but land-use practices and natural drivers can only be distinguished by models, not observations (Pongratz et al., 2021).

6.1.2. Carbon pools, turnover, and disturbances

Carbon is stored across aboveground biomass (stems, branches, foliage), belowground biomass (roots), dead organic matter (litter and deadwood), and SOC. Globally, research suggests that forests store roughly 42% of their carbon in live biomass, 44% in soils, 8% in deadwood, and 5% in litter, although these proportions differ markedly among biomes (Pan et al., 2011). Tropical forests store a substantially larger proportion of their carbon in biomass, whereas boreal forest carbon stocks are predominantly located in soils (Pan et al., 2011). Tropical forests contain roughly similar amounts of carbon in vegetation and soils (120 and 123 t C ha^{-1}, respectively), whereas boreal forests store substantially more carbon in soils than in vegetation (344 versus 64 t C ha^{-1}) (Prentice et al., 2001). This biome-level contrast has management implications: where soils constitute a dominant carbon pool, as in boreal forests, management should place particular emphasis on protecting soil carbon and minimizing disturbances to organic horizons, rather than focusing primarily on aboveground biomass accumulation (Mayer et al., 2020; Mäkipää et al., 2023). These pools also differ markedly in turnover time. Foliage typically turns over within one growing season to a few years (van Ommen Kloeke et al., 2012), while fine roots commonly turn over on timescales of roughly 1–3 years (Gill and Jackson, 2000). Deadwood can retain carbon for decades or, in some cases, centuries (Harmon et al., 2020), whereas litter generally cycles more rapidly. SOC spans the widest range, with different fractions cycling over timescales from days or years to centuries or millennia (Trumbore, 1997). Disturbances redistribute carbon among pools and can reverse removals. Dye et al. (2024) recently highlighted that climate change alters disturbance regimes in ways that challenge long-term forest carbon storage goals and increase uncertainty around future sink strength. Because deadwood and litter can be substantial and dynamically important, especially after disturbance, methods for quantifying necromass and decomposition rates are increasingly treated as integral to carbon accounting (Herrmann et al., 2015; Russell et al., 2015). Belowground pools deserve particular attention in A/R, because changes in soil carbon are often slower and more variable than changes in aboveground biomass and may take decades to become detectable. Their magnitude and even direction depend strongly on prior land use, climate, soil properties, species, and management; for example, Laganière et al. (2010) found that afforestation tends to increase SOC more strongly on former croplands than on pastures, with changes unfolding over multi-decadal timescales.

6.2. Out-of-forest storage

Out-of-forest storage matters for later carbon outcomes because once biomass leaves the stand, its CDR value depends on how long storage persists, how well downstream pathways are governed, and whether those pathways can be tracked credibly. Out-of-forest storage occurs when harvested biomass is transferred into HWP pools, directly placed into long-term storage through biomass burial, converted into more durable carbon forms (e.g., biochar), or used in processes that combine energy production with CO_2 capture and geological storage, such as Bioenergy with Carbon Capture and Storage (BECCS). Out-of-forest storage can extend the residence time of harvested carbon and, where the forest subsequently regrows, allow additional atmospheric CO_2 to accumulate in the replenishing stand. The resulting CDR value depends on both the durability of downstream storage and the rate and extent of forest carbon recov-

ery, as well as life-cycle emissions and the accounting boundary. Harvested biomass transferred into short-lived products such as paper and paperboard may temporarily delay carbon release and contribute to HWP accounting or circular material use, but such short-lived storage is not treated here as CDR-relevant durable storage (Braun et al., 2016; Brunet-Navarro et al., 2017).

6.2.1. Harvesting and transfer to downstream carbon pools

Harvesting forms the transition between in-forest carbon storage and downstream biomass pathways. Carbon removed in harvested biomass may enter HWPs, processing residues, bioenergy, or other storage and use pathways. The resulting carbon outcome depends on product allocation, processing losses, residue fate, product lifetime, and end-of-life treatment (Rüter et al., 2019; Kayo et al., 2021; Zhao et al., 2022). Globally, the transfer of carbon into durable HWPs was estimated at approximately 801 Mt CO_2 yr^{-1} over 2013–2022; after accounting for the re-release of CO_2 through product decay, the net sink from durable HWPs was approximately 332 Mt CO_2 yr^{-1} over the same period (Smith et al., 2024). These estimates should not, however, be interpreted as wholly additional to A/R or forest-management removals, because some double counting between HWP storage and forest-based CDR estimates may occur. Only part of the harvested biomass typically ends up in final wood products; another fraction is lost during processing or enters residue streams such as bark, offcuts, and sawdust, with different carbon outcomes depending on how these materials are used or treated. Carbon benefits therefore cannot be inferred from harvest volumes alone. Residues may remain on site, be rapidly oxidised, or enter downstream uses such as bioenergy or more durable storage pathways. Carbon accounting must therefore track this redistribution across forest, product, residue, and atmospheric pools. The HWP pool is explicitly recognised in greenhouse gas accounting, with emissions and removals commonly represented using first-order decay functions and product-specific lifetimes (Kayo et al., 2021). The magnitude and duration of HWP storage depend on how much harvested biomass reaches long-lived products rather than residues, short-lived goods, or rapid combustion (Skog, 2008; Johnston and Radeloff, 2019; Zhao et al., 2022). Net outcomes therefore depend on harvest intensity as well as the full life cycle of harvested biomass, including product lifetimes, end-of-life treatment, and the duration of carbon storage in HWPs (Geng et al., 2017; Rüter et al., 2019). Whether these downstream carbon pathways can be tracked accurately over relevant time horizons is itself a major accounting challenge, especially where product lifetimes, recycling, and end-of-life fate are uncertain or weakly governed.

6.2.2. Long-lived construction products

Wood used in buildings may contribute to durable carbon storage only where it is incorporated into building elements with explicitly accounted service lives and replacement cycles, rather than in movable or short-lived products, such as furniture, whose retention cannot be assured over CDR-relevant time horizons (Francart et al., 2021). In that sense, the strongest case is not for wood products in general, but for wood embedded in long-service-life building components, especially where the building assessment framework specifies the reference study period and how shorter-lived elements are replaced over time (Hoxha et al., 2020). Methodological clarity is therefore essential if building-related biogenic carbon storage is invoked in CDR claims, because conclusions depend strongly on assumptions about service life, replacement, end-of-life fate, and forest regrowth. Accordingly, not all harvested wood products should be treated alike in CDR accounting.

6.2.3. Biochar, Bioenergy with Carbon Capture and Storage, and biomass burial

Several downstream biomass pathways can extend the storage of carbon initially captured through A/R, including biochar, BECCS, and biomass burial. Biochar is produced by pyrolysis of biomass and can be applied to soils or incorporated into building materials (Legan et al., 2022). Woolf et al. (2010) estimated a maximum sustainable technical mitigation potential of 1.8 Pg CO_2-C-equivalent yr^{-1}, equivalent to about 12% of then-current anthropogenic CO_2-C-equivalent emissions, while emphasizing uncertainties and sustainability constraints associated with biomass supply and production. Its net CDR value depends on life-cycle emissions from feedstock collection, transport, preprocessing, pyrolysis, co-product use, and application, as well as storage durability, which varies with feedstock, pyrolysis conditions, and soil environment (Jindo and Sonoki, 2019; Adhikari et al., 2024; Azzi et al., 2024). From a CDR and carbon-crediting perspective, biochar is best treated as a durability-graded storage pathway, such that the quality and magnitude of credited removals should reflect measured or conservatively modeled persistence rather than assuming permanence.

BECCS combines biomass conversion for energy with CO_2 capture and geological storage (Schaber et al., 2026). Within an A/R process chain, photosynthesis provides the initial atmospheric CO_2 uptake, while BECCS transfers part of that biomass carbon into a longer-lived geological reservoir (Swoboda and Oschlies, 2025). Whether this integrated pathway delivers net CDR depends on additionality and the timing of biomass uptake, the counterfactual fate of the biomass, life-cycle emissions, capture efficiency, and geological-storage integrity (Cummings et al., 2025; Swoboda and Oschlies, 2025); life-cycle assessments are also sensitive to methodological choices and data quality across these stages (Duval-Dachary et al., 2023). The energy-system benefit of BECCS, including which energy source it substitutes, concerns the emission reduction realm and thus does not contribute to the CDR pathway.

Biomass burial similarly aims to extend carbon storage by placing woody material under conditions that suppress decomposition, such as low oxygen availability and low-permeability cover materials (Zeng et al., 2024). In an A/R context, it is most relevant for low-value biomass that would otherwise decompose or be burned, including thinning residues, harvest residues, sawmill residues, or other underutilized woody material (Yao, 2024; Johnson et al., 2025). Its CDR value depends on whether the stored biomass is additional rather than diverted from longer-lived uses, on emissions from collection, transport, construction, and burial, and on demonstrated storage durability, including limited decay and methane leakage (Zeng et al., 2024; Johnson et al., 2025). Large-scale deployment may also create trade-offs through nutrient export, biomass availability, and competition with alternative biomass uses.

Across all three pathways, the relevant comparison is not simply whether biomass carbon can be stored downstream, but whether doing so provides greater net and durable CDR than alternative uses or continued in-forest storage after accounting for counterfactual carbon fate, life-cycle emissions, competing biomass demands, and reversal risks.

6.2.4. Cascading use

Cascading (or cascading use) refers to the sequential use of wood in higher-value, longer-lived applications, such as structural timber, engineered wood products, furni-

ture, or wood-based panels, before subsequent reuse, recycling, and eventual energy recovery or disposal. From a CDR perspective, its relevance lies primarily in extending the residence time of biogenic carbon and potentially transferring that carbon into increasingly durable forms of storage. Forster et al. (2023) suggest that cascading wood use can prolong carbon storage in products, although the resulting storage duration depends on actual reuse, recycling, and end-of-life pathways rather than on the designation 'cascading' itself. Taskhiri et al. (2019) likewise show that cascade-oriented allocation can improve resource efficiency relative to linear use patterns, although such broader environmental benefits should be distinguished from CDR. Whether cascading ultimately contributes to durable CDR therefore depends on the cumulative duration of storage across successive product uses and on the final fate of the carbon, including whether it is eventually transferred into a more durable storage pathway or returned to the atmosphere. The associated requirements for long-term management, tracking, and end-of-life responsibility are not unique to cascading, but form part of the broader permanence and MRV challenge for non-permanent carbon storage. This distinction matters because some biomass pathways reduce emissions relative to alternatives without constituting CDR in the strict sense. Some downstream biomass uses may additionally provide avoided-emission benefits through material or energy substitution (Sathre and O'Connor, 2010; Geng et al., 2017; Hoxha et al., 2020), which do not constitute CDR, and thus, are not considered here (Swoboda and Oschlies, 2025). The CDR-relevant downstream pathways instead differ in storage duration, reversal risk, and measurability, requiring MRV to distinguish among carbon pools and storage forms rather than treating forest-derived carbon as a homogeneous stock.

7. Monitoring, Reporting, and Verification

Monitoring, reporting, and verification are the accounting backbone of A/R-as-CDR. Through a multi-step process, MRV links ex-ante expectations (what a project says it will remove) to ex-post evidence (what it demonstrably removed), while making uncertainty, reversals, leakage, and out-of-forest fates explicit and providing information that can support adaptive management when observed outcomes deviate from expectations. While carbon quantification remains the basis for CDR claims, monitoring should also track ecological and social conditions that affect project performance, safeguards, and the durability of stored carbon. The central challenge is not only to define what should be measured, but to determine whether these variables can be measured repeatedly, accurately, and affordably enough to support credible net-removal claims over project-relevant timescales. In practice, most MRV architectures for land-sector carbon build on IPCC good practice guidance defining, transparency, accuracy, consistency, completeness, and comparability (TACCC) implemented through a combination of field measurements, models, and remote sensing, with rigorous QA/QC (Quality Assurance / Quality Control) and independent checks (IPCC, 2003; Aalde et al., 2006b; Domke et al., 2019). Within the process chain, MRV is not an external audit added at the end; it safeguards that earlier site, species, management, and product decisions can ultimately translate into defensible net-removal claims.

7.1. Principles of MRV design during site selection

MRV design is most robust when integrated from the outset of project planning, so that baseline conditions, accounting boundaries, and monitoring requirements are established before intervention. Monitoring approaches may subsequently be refined or adapted as new data, methods, or project conditions emerge, but retrospective

reconstruction of baseline conditions generally introduces greater uncertainty. During site selection, a carbon budget assessment (i) defines the accounting boundary (land unit, pools, time horizon), (ii) screens the feasibility of measuring key pools (biomass, deadwood, soil, and relevant non-CO_2 gases), and (iii) pre-designs the sampling/monitoring strategy to achieve target precision at an acceptable cost. MRV guidance recommends matching method complexity to the scale of expected carbon change and reversal risk, which means higher-risk or more heterogeneous sites may require denser sampling, stronger stratification, or better disturbance monitoring than relatively uniform low-risk sites (Aalde et al., 2006a; Köhl et al., 2011; Ogle et al., 2019). A key deliverable at this stage is a stratification scheme: the partitioning of the project area into relatively homogeneous units based on factors such as land cover, soils, topography, management regime, and disturbance risk, so that the relevant variables, measurement intensity, and assessment methods can be defined appropriately for each unit. In practice, a project may be biophysically attractive yet MRV-infeasible if key pools or disturbance processes cannot be measured with sufficient confidence within realistic budget and staffing constraints. More broadly, MRV design must establish how reliably each method can measure and extrapolate across those units, including its accuracy, uncertainty, and spatial representativeness. This applies equally to field-based inventories, soil sampling, and remote sensing alike. Where remote sensing is used for activity data or biomass estimation, for example, statistically robust accuracy assessment and area estimation are essential to avoid biased carbon estimates (Olofsson et al., 2014).

The degree of project-specific measurement required is itself a design choice. In addition to intensive project-level MRV, removals may be estimated using standardized factors, models, or performance benchmarks developed for defined land-use, ecological, or management classes. Such approaches can reduce transaction costs by shifting part of the measurement burden from individual projects to the development and validation of representative default values or benchmarks. They do not eliminate MRV, however: eligibility and implementation must still be demonstrated, underlying factors require periodic validation, and disturbances or reversals may still need to be monitored. The appropriate balance between standardized and project-specific approaches therefore depends on site heterogeneity, expected removal magnitude, uncertainty, and the level of conservativeness required for crediting.

7.2. Monitoring

7.2.1. Baseline determination and initial carbon assessment

For A/R-as-CDR, the appropriate reference against which removals are quantified can involve both the initial carbon stocks present at project establishment and, where required for attributing additionality, a counterfactual trajectory describing how those stocks would likely have changed without the intervention. Measuring initial stocks prevents pre-existing carbon from being attributed to the project, which is particularly important for soils and other legacy carbon pools where substantial carbon stocks may remain from previous ecosystems or land uses and should not be counted as newly removed carbon merely because they persist after A/R establishment. A counterfactual trajectory, by contrast, is needed where carbon changes that would have occurred in the absence of A/R must be separated from project-induced removals. This issue is particularly consequential in carbon crediting, where credited removals are intended to represent changes additional to the no-project scenario. Where a counterfactual baseline is used, credited removals are calculated relative to this no-project trajectory, making baseline setting central to the integrity of the resulting carbon-removal

claims. A key challenge is that past land-use trends do not necessarily predict future land-use decisions well, as historical patterns may reflect commodity prices, policies, tenure arrangements, infrastructure access, or climate conditions that later change. Research also show that coarse benchmark baselines based on 'typical' regional practice or average carbon stocks can introduce systematic bias when they are applied across ecologically heterogeneous areas (Randazzo et al., 2023; Nolan et al., 2024). For example, if sites with different rainfall, elevation, productivity, or species composition are grouped together, a project on a naturally high-carbon site may appear to outperform the baseline even without meaningful management change, whereas projects on naturally lower-carbon sites may be disadvantaged. Likewise, assuming lower carbon uptake, greater degradation, or weaker regrowth in the counterfactual than is realistically supported by evidence inflates the credited removal. Evaluations of forest carbon crediting programs emphasize why baselines should be empirically grounded and conservative. In this context, a conservative baseline does not mean an arbitrary low estimate; it means a counterfactual constructed in a way that avoids overstating credited removals when evidence is uncertain. Analyses of California's forest offsets program, for example, have documented systematic over-crediting linked to the design of regional benchmark baselines and to limited evidence that credited projects actually implemented management changes beyond what would likely have occurred anyway (Badgley et al., 2022; Stapp et al., 2023). This matters because if credited projects do not demonstrably change management or carbon outcomes relative to the counterfactual, then the credited removals are not fully additional. Probst et al. (2024) similarly show that credited quantities can diverge from achieved effects when baseline assumptions and quantification methods are not conservative.

7.2.2. Total carbon storage

Carbon storage should be reported separately for (a) forest ecosystem pools and (b) harvested or other out-of-forest pools. Where harvested wood products are included within the applicable accounting framework, they are tracked separately using harvest and product-allocation data together with product-specific decay assumptions. However, IPCC guidance was developed primarily for national GHG inventories, whereas project-level crediting standards specify their own requirements for pool inclusion, measurement, uncertainty, and conservative exclusion. These methodologies often draw on IPCC methods and default factors but adapt them to project-level quantification and verification; for example, Verra VM0047 (Verra, 2025), Gold Standard's A/R methodology (The Gold Standard Foundation, 2024), and ACR's A/R methodology (American Carbon Registry, 2017), differ in which forest carbon pools must or may be quantified (Ogle et al., 2019). All material carbon pools should, in principle, be accounted for using pool-specific measurement or modelling procedures. A pool may be omitted only where the applicable accounting framework permits this and where transparent and verifiable evidence demonstrates that its exclusion is conservative and cannot increase the estimated net removals (IPCC, 2003; Aalde et al., 2006b; Domke et al., 2019). Aboveground tree biomass is typically estimated from repeated plot inventories using allometric equations based on tree diameter, height, and wood density; in tropical forests, pantropical equations and locally calibrated variants are widely used (Chave et al., 2014). Belowground tree biomass is often inferred from root-to-shoot ratios or site-specific models linked to aboveground biomass. Deadwood and litter are estimated either from repeated field measurements or from gain-loss and decay models, while soil organic carbon is monitored through stratified soil sampling and repeated resampling over multi-year intervals (Domke et al., 2019; Ogle et al., 2019).

Following disturbance, deadwood often becomes a major carbon pool and may be overlooked without dedicated sampling; methodological reviews therefore provide specific approaches for deadwood quantification and decomposition modelling (Russell et al., 2015). Likewise, SOC responses to afforestation and reforestation are heterogeneous and often unfold over decadal timescales. Laganière et al. (2010) show that SOC increases are frequently observed where forests are established on former croplands, but the magnitude and timing of change vary with climate, tree species, and the type of land use preceding afforestation. Soil monitoring design is critical as changes depend on sampling depth and the soil fractions considered. There is no universal sampling depth for terrestrial forest carbon accounting: IPCC guidance commonly uses 30 cm as a reference depth for mineral soils, but substantial carbon stocks and management-induced changes can occur below this depth, and deeper sampling may therefore be warranted depending on soil type, rooting depth, prior land use, and the processes affected by the A/R intervention (Aalde et al., 2006b; Shi et al., 2013; Domke et al., 2019). Shallow sampling can underestimate soil carbon accumulation following afforestation (Shi et al., 2013), highlighting the importance of selecting a depth appropriate to the expected vertical distribution of change. Sampling depth should consequently be defined ex-ante and applied consistently across baseline and subsequent monitoring.

Out-of-forest pools, on the other hand, require a different type of accountability. In credible CDR accounting, storage in HWPs requires strong product management and regulatory accountability, particularly where long-lived building elements are concerned, so that assumed storage durations and end-of-life pathways are not merely theoretical. Comparative reviews and model application show that HWP carbon estimates are highly sensitive to assumptions about product lifespan, recycling, and end-of-life treatment (Brunet-Navarro et al., 2016, 2017), so product-related storage claims are only as credible as those assumptions and the governance behind them.

7.2.3. Emissions from A/R (re-)establishment and management

MRV for net CDR should also include GHG emissions of the project associated with establishment and ongoing operations, including CO_2, CH_4, and N_2O where relevant, often using LCA methods, so that the reported outcome is not gross sequestration but a net climate effect. Relevant emission sources can include any activity for the implementation and maintenance of the A/R intervention and may primarily arise due to nursery production, site preparation machinery, transport, planting, weeding/fertilisation, road maintenance, thinning/harvesting operations, and (where applicable) post-harvest processing of biomass into HWPs, biochar, or BECCS feedstocks, together with the associated energy use (Hájek et al., 2024; Saharudin et al., 2024). These activities may generate fossil CO_2 emissions from energy use as well as CH_4 or N_2O emissions associated with biomass treatment, fertilisation, and changes in soil processes. A recent study by Yao and Zhang (2025) argues that integrating LCA more directly into MRV improves comparability across project configurations and downstream carbon-management options and helps prevent claims of net-negative emissions that ignore supply-chain emissions or timing effects. Including these sources is therefore essential if later claims are to reflect net rather than gross climate benefit.

7.2.4. Sequential monitoring

Sequential monitoring typically combines: (i) repeated field measurements on permanent plots, (ii) activity data updates (where land-cover change is possible), and (iii) remote sensing to scale and update biomass or disturbance impacts to provide the

time-series evidence needed to determine whether expected carbon accumulation continues, stalls, or reverses through time. MRV guidance consistently favours combining field plots with remote sensing because plots provide calibration and error checking, while remote sensing improves spatial coverage and disturbance detection across the full project area (Lallo et al., 2017; Espejo et al., 2020). Remote sensing is increasingly capable of annual or near-annual disturbance detection and biomass tracking, but MRV-grade use still hinges on statistically sound validation and uncertainty quantification. Research evidence suggests that annual high-resolution biomass products can improve restoration MRV by detecting spatially uneven growth and disturbance between field campaigns (Olofsson et al., 2014; Atzberger et al., 2025). And it is key to use the same remotely sensed source over time as resolution and accuracy vary greatly across products (Huang et al., 2015, 2017; Duncanson et al., 2019; Tang et al., 2021). Remote sensing can improve spatial and temporal coverage, but it does not eliminate the need for ground validation and may still struggle to resolve some belowground or product-pool changes.

7.2.5. Net carbon storage / Net removal quantification

Net carbon storage (or net CO_2 removals) should be reported as the change in eligible in-forest and out-of-forest carbon stocks relative to the applicable reference or baseline, minus relevant project-related CO_2 emissions, while explicitly accounting for baseline, leakage, and reversals. In a stock-change approach, ecosystem CO_2 losses through respiration and decomposition are already reflected in observed changes in carbon stocks and should therefore not be subtracted separately. Flux-based measurements such as eddy covariance can provide complementary information on net ecosystem CO_2 exchange by integrating photosynthetic uptake, ecosystem respiration and lateral fluxes over time. Leakage, or indirect land-use change, here referring specifically to project-induced displacement of land use, resource extraction, or associated emissions outside the accounting boundary, is an important component of credible MRV because displaced activities can partially or fully offset on-site carbon gains. In A/R, this may occur where agriculture, grazing, fuelwood collection, or timber extraction are shifted elsewhere as a result of the intervention (Chapin et al., 2006; Ogle et al., 2019). Such displacement is not necessarily confined to areas immediately surrounding a project: at larger scales, land-use changes can be transmitted across regions, countries or even continents through commodity markets and international trade, creating indirect land-use change that may offset part of the apparent local or national carbon benefit (Meyfroidt et al., 2010; Lambin and Meyfroidt, 2011; Meyfroidt et al., 2013; Hong et al., 2022). Leakage should therefore be assessed systematically and quantified wherever possible; where precise quantification is not feasible, conservative deductions should be applied rather than assumed away. Filewod and McCarney (2023) show that such leakage can materially reduce or even offset on-site carbon gains when displaced activities simply shift outside the project boundary rather than disappearing. Although conceptually straightforward, leakage is often difficult to quantify in practice, especially where displaced activities are diffuse, informal, or occur outside well-monitored boundaries.

7.2.6. Environmental and social monitoring

Carbon monitoring alone does not capture all factors that determine whether A/R projects remain ecologically functional, socially supported, and durable over time. The need for broader outcome monitoring is also evident in current reforestation practice: in a global survey of intermediary reforestation organizations, livelihoods and biodiversity conservation were more commonly reported goals than carbon, and

although 87% of organizations reported requiring monitoring beyond the first year, systematic public reporting of project-level outcomes remained uncommon (Schubert et al., 2026). Environmental monitoring should therefore complement carbon accounting by tracking project-relevant ecological outcomes and risks, which may include vegetation composition and diversity, natural regeneration, invasive species, soil condition, hydrology, erosion, habitat attributes, and disturbance pressures. Environmental monitoring should also consider whether project implementation displaces environmental pressures beyond the project boundary, for example where land-use changes or reduced domestic production increase reliance on imported commodities and thereby shift deforestation, fertilizer use, pesticide use, or other impacts to other regions (Fuchs et al., 2020). The appropriate indicators should follow from the ecological objectives and risks identified during project design rather than be treated as a universal checklist. Restoration standards similarly emphasize monitoring ecological recovery against defined reference conditions and using observed outcomes to support adaptive management (Gann et al., 2026).

Social monitoring is likewise important because changes in livelihoods, resource access, tenure security, benefit distribution, participation, or conflict can affect continued local support for an A/R intervention and thereby influence reversal and non-delivery risk (Allgood et al., 2025). Relevant indicators may therefore include livelihood effects, access to land and forest resources, distribution of project benefits and burdens, tenure or boundary disputes, participation in decision-making, grievances, and stakeholder perceptions of project outcomes. These variables should ideally be assessed against pre-project conditions and monitored repeatedly, with indicators developed together with affected groups where feasible. Participatory monitoring can additionally support local learning and adaptive management, while requiring appropriate safeguards for privacy, data sovereignty, and representation (Gann et al., 2026).

7.3. Reporting

Reporting should enable a technically competent third party to reproduce carbon estimates, trace each data input and estimated carbon flux to its underlying source, and understand how uncertainty and methodological choices affect the results. This requires transparent spatial documentation of the project, including georeferenced project and accounting boundaries that allow independent assessment of land cover, project implementation, disturbance, and other spatially explicit claims. Such spatial information is not consistently publicly available (Schubert et al., 2026). Where compatible with legitimate land-tenure, privacy, and safeguarding constraints, these spatial data should be made publicly accessible in machine-readable form to facilitate independent verification.

Consistent with IPCC good practice (IPCC, 2003; Domke et al., 2019), an ideal reporting package should typically include: (1) project description and spatial delineation of the project and accounting areas (georeferenced boundaries, maps, monitoring-unit definitions, land status, management actions, and monitoring schedule); (2) baseline rationale and evidence (counterfactual land use, expected carbon-stock and carbon-flux changes over time, and justification of assumptions); (3) measurement, estimation, and data-processing approaches (field plot design, measurement protocols, allometric equations and their domain of validity, remote-sensing products, processing workflows, and parameter sources); (4) uncertainty quantification and propagation (sampling error, model and allometric error, classification and area-estimation error for remote sensing, and how these combine to

yield confidence intervals for credited removals); and (5) change logs that explicitly record any methodological updates, such as sensor changes, updated allometric equations, revised measurement protocols, or revised partitioning of monitoring units, together with how time-series consistency is maintained. Best practice in land-cover and remote-sensing components is to report accuracy assessment and unbiased area estimation, rather than only map accuracy, because map error can otherwise translate into biased carbon totals (Olofsson et al., 2014). Because A/R-as-CDR claims hinge on durability, reporting should also include disturbance documentation, attribution and quantification of resulting stock changes, and the treatment of carbon release and post-disturbance recovery. Where harvested wood products or other out-of-forest pools are credited, reporting should disclose product allocation assumptions, lifetime and decay models, recycling and end-of-life pathways, and how double counting is avoided across accounting boundaries (Brunet-Navarro et al., 2016).

Finally, the credibility of MRV depends increasingly on robust data stewardship so reported carbon outcomes are reproducible, attributable, and durable. Reports should therefore include a data management and availability statement describing where raw data, processed data, and code are archived, what metadata standards are used, and how versions are controlled. For MRV to be credible, access to the underlying raw data is essential, because otherwise independent re-analysis and verification are not possible. Applying FAIR (Findable, Accessible, Interoperable, Reusable) principles improves transparency, reproducibility, and long-term usability, especially for long-lived projects with repeated monitoring cycles (Wilkinson et al., 2016). Reproducible computational workflows, including clear scripts, parameter files, and versioned inputs, can further reduce hidden analyst degrees of freedom and strengthen verification-readiness (Peng, 2011). The reporting burden itself may become a feasibility constraint, particularly for small-scale and long-lived projects that rely on repeated measurements, versioned workflows, and data stewardship across institutional changes.

7.4. Verification

Verification is the stage at which the entire process chain is tested against evidence: it assesses whether the cumulative effects of upstream decisions are sufficient to justify the removals that are ultimately claimed. Verification independently evaluates whether reported removals are (a) methodologically compliant and (b) evidentially supported, with an explicit focus on whether plausible errors, biases, or omissions could materially alter the credited outcome. In land-sector MRV, verification typically examines (i) data integrity and QA/QC, (ii) plot design and field protocols, (iii) the appropriateness of biomass-estimation models and related measurement approaches, (iv) how baselines, uncertainty, leakage, and disturbances have been defined, justified, and applied in the accounting, and (v) whether reported spatial information and mapped project areas are consistent with field conditions and other independent evidence. In forest CDR, where carbon fluxes are spatially heterogeneous and reversal risk is intrinsic, verification must go beyond box-ticking or merely checking whether the required information has been reported; it asks whether the reported information is reliable, traceable, and supported by field conditions and independent evidence. It is best understood as a structured attempt to reduce two persistent asymmetries: information asymmetry, whereby project operators know more about field realities than outside assessors, and model asymmetry, whereby carbon results depend on choices about area partitioning, biomass-estimation models, baselines, and uncertainty treatment that may all appear technically defensible while still biasing results in a particular direction. REDD+ MRV experience shows

that MRV depends on agencies able to maintain monitoring systems, manage data transparently, and submit claims to independent scrutiny (Herold and Skutsch, 2011).

At a practical level, verification typically combines desk-based re-performance (re-computing carbon estimates from raw inputs) with field-based triangulation (auditing plot networks, remeasuring subsamples, and checking that mapped strata correspond to on-the-ground conditions). A robust verifier not only confirms that numbers exist; they test whether numbers are traceable. That implies systematic checks on: plot design and representativeness; measurement protocols and QA/QC; chain-of-custody for data edits; and whether sampling intensity meets stated precision targets. Where remote sensing contributes to activity data or biomass estimates, verification should explicitly evaluate accuracy assessment and unbiased area estimation, because map error can translate directly into biased carbon totals if handled incorrectly (Olofsson et al., 2014).

Secondly, verification must interrogate counterfactual dependence, especially baselines and leakage. The credibility of credited removals is only as strong as the defensibility of what would have happened otherwise, and a growing body of literature show that baseline design can systematically inflate carbon claims when baseline assumptions, benchmark categories, or related accounting approaches are weakly supported by evidence. Verification therefore needs to evaluate baseline justification as a falsifiable claim: Does the baseline align with observed regional trends? Are relevant constraints and land-use drivers realistically represented? Are the resulting claims robust to sensitivity analysis? Recent assessments of improved forest management and offset protocols by Haya et al. (2023) repeatedly identify weak additionality tests, optimistic baselines, under-specified leakage treatment, and poorly defended durability claims as recurring failure points in practice.

Verification must also address the durability of stored carbon in a manner consistent with the accounting framework. In conventional project-based crediting, this generally requires repeated monitoring of whether previously stored carbon remains in place and whether reversals are detected and quantified. Alternative duration-based or option-based approaches may instead assign projects an explicit storage horizon and adjust credited removals accordingly, shifting verification toward confirming that the project meets the conditions associated with that durability class. Where permanence is managed through reversal-risk mechanisms such as buffer pools, verification also needs to assess how quickly losses are detected and whether the buffer is calibrated to observed and anticipated hazards. Evidence from the California forest offset program suggests that buffer provisions can be insufficient relative to empirical risk, implying that 'verified today' does not necessarily mean 'durable tomorrow' unless reversal risks are quantified and adequately covered (Badgley et al., 2022). In high-quality verification, durability should therefore be treated explicitly, either as a quantified reversal risk requiring ongoing management or as a defined storage duration reflected in the accounting and value of the credited removal.

Finally, project planners and verification frameworks must acknowledge the structural limits of third-party verification. Giles and Coglianese (2025) argue that third-party auditing, particularly when verifiers are selected and paid by the entities they assess, cannot by itself guarantee offset credibility, and that stronger governance, transparency, and accountability structures are needed alongside technical MRV rigor. Put simply: verification increases confidence, but it does not eliminate uncertainty or incentive problems; credibility is highest when verification is embedded within sys-

tems that mandate data transparency, conservative accounting, repeat monitoring, and enforceable consequences for misreporting.

8. Conclusions

Afforestation and reforestation are currently the major anthropogenic route by which atmospheric CO_2 is removed from the atmosphere and stored for some period of time. The credibility of A/R-as-CDR does not begin with planting and end with tree survival; it depends on whether carbon remains additional, measurable and durable over decades in landscapes exposed to disturbance, changing climate, competing land uses and shifting governance conditions. To account for the various stages involved in A/R, the process-chain perspective herein presented matters because weaknesses at one stage can propagate through the chain and undermine later carbon outcomes. Carbon gains can be overstated by implausible baselines, eroded by leakage, and lost abruptly through fire, drought, pests or land-use decisions. Even where forest recovery is successful, the climate impact of the resulting carbon stock depends on how long it persists, while the credibility of associated CDR claims depends on how rigorously the carbon stock is monitored and verified. The relevant question for meaningful climate change mitigation through A/R-as-CDR, therefore, is not how many hectares are planted, but whether the intervention produces net, long-lasting and socially legitimate carbon removals once the full carbon balance from photosynthetic uptake and later product usage are taken into account.

A central contribution of this review is therefore to reposition A/R-as-CDR away from a simplified tree-planting narrative and toward a chain of coupled decisions in which early choices propagate into later carbon outcomes. Site characteristics influence species suitability; nursery and seed-system quality shape establishment success; preparation and maintenance affect survival and resilience; harvesting and product allocation determine durability of the carbon sequestered; and MRV determines whether any claimed removals are evidentially supported. These linkages create integrity-critical interfaces across the process chain: site and species choices shape establishment success and disturbance exposure; establishment quality affects later management requirements; and management, harvesting, and product allocation influence both carbon durability and the removals that can ultimately be verified. That is precisely why each stage of the A/R process chain must be judged not in isolation, but by how it impacts the carbon outcomes of later stages. For research and practice alike, this implies that high-quality A/R design must integrate forestry and ecological restoration principles with carbon accounting, tenure and rights considerations, as well as long-term risk management from the outset. If rigorous and integrated planning, implementation, and MRV processes are used, A/R can play a meaningful role in future climate change mitigation. When well designed, it may also generate co-benefits, including biodiversity enhancement, ecosystem recovery, improvements in soil stability, and water regulation. These benefits strengthen the case for careful deployment, not for inflated expectations. A/R is not a fast, fungible or universally durable substitute for emissions reduction. It is a biologically mediated, disturbance-prone, and governance-dependent intervention whose outcomes remain heterogeneous and whose failures can take decades to become fully visible.

Ultimately, A/R-as-CDR should complement, rather than substitute for, rapid and sustained emissions reductions. The process-chain framework developed here provides a structured basis for identifying where A/R carbon outcomes are shaped, constrained, or placed at risk across the lifetime of an intervention. Future work

should build on this approach by quantifying these cross-stage dependencies, identifying which interfaces most strongly determine net CDR outcomes across different A/R systems, and developing integrated ecological, social, operational, and carbon-accounting indicators that can be applied throughout the project lifetime. Because removals are slower to accumulate, more vulnerable to later carbon release, and often harder to verify than avoided emissions, the safest and most credible climate strategy remains the rapid and sustained reduction of gross greenhouse gas emissions, including halting deforestation.

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Data accessibility statement

No new datasets were generated or analyzed in this study. All sources used are cited within the manuscript.

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