

Forest Climate Mitigation Across Time Horizons: Reconciling Carbon Sequestration, Harvesting, Wood Substitution, and Bioenergy Under Dynamic Accounting

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ABSTRACT

Forests are central to climate mitigation, but their net climate effect depends on how ecosystem sequestration, harvesting, harvested wood products, material substitution, and bioenergy interact through time. This critical integrative review reassesses a supplied forest-sector evidence base with emphasis on temporal trade-offs, accounting boundaries, management intensity, product lifetimes, substitution assumptions, and forest productivity. The literature shows that apparently conflicting conclusions are often conditional rather than irreconcilable. Reduced harvesting commonly strengthens near-term ecosystem carbon retention, whereas production-oriented strategies can generate larger long-run benefits only when additional biomass is produced sustainably, allocated efficiently, and demonstrably displaces carbon-intensive materials or fossil energy. Substitution benefits are highly sensitive to the counterfactual product, market additionality, future decarbonization, and whether foregone forest sequestration is fully counted. Dynamic life-cycle studies further

show that the timing of biogenic emissions and removals can change the relative performance of management strategies. We therefore propose a four-ledger framework integrating ecosystem carbon, harvested-product storage, avoided fossil and process emissions, and temporal opportunity costs. Break-even time and the required displacement factor are used as complementary decision metrics. The review concludes that no single harvest rule is climate-optimal across contexts; robust assessment requires explicit baselines, policy-relevant time horizons, full forest-sector accounting, and sensitivity testing.

Keywords: forest climate mitigation; forest carbon sequestration; wood product substitution; bioenergy; displacement factors; dynamic life cycle assessment; temporal trade-offs

1. INTRODUCTION

Forests are simultaneously ecosystems, carbon reservoirs, renewable-resource systems, industrial feedstock bases, and energy sources. This multifunctionality makes climate assessment difficult because

management changes several carbon pathways at once. A forest left unharvested may continue accumulating and retaining carbon, while harvesting can transfer carbon into products that store it and may replace more emission-intensive materials. Harvested biomass may also be used for energy, where the outcome depends on the displaced fuel, conversion efficiency, supply-chain emissions, regrowth, and the forest trajectory that would have occurred without harvest. These interactions explain why studies can reach different conclusions about whether conservation, lower harvesting, or production-oriented management provides greater mitigation (Schlamadinger & Marland, 1996; Werner et al., 2010; Gustavsson et al., 2021).

Time is a central source of this disagreement. Climate policy is constrained by the need to reduce atmospheric greenhouse-gas loading over the coming decades, whereas forestry decisions involve rotations, regrowth, product lifetimes, and landscape transitions that can extend for a century or more. A strategy that appears beneficial at a distant endpoint may first increase atmospheric carbon for decades. Dynamic analyses therefore show that rankings can change with the assessment horizon: conservation or lower harvest may perform better initially, while production-oriented strategies can overtake later if sustained productivity and substitution benefits are sufficiently strong (Gustavsson et al., 2017; Peñaloza et al., 2019; Skytt et al., 2021).

Substitution adds another layer of conditionality. Wood can avoid emissions when it replaces steel, concrete, fossil fuels, or other high-emission alternatives, but the displacement benefit is not an intrinsic property of wood. It depends on the product being displaced, market additionality, energy systems, product lifetime, and future decarbonization (Sathre & O'Connor, 2010; Harmon, 2019; Leturcq, 2020). Baseline choice is equally important. Comparing active management with no harvest, business as usual, or another management trajectory changes the opportunity cost assigned to

harvesting. The same physical intervention can therefore produce different modeled mitigation outcomes because the counterfactual, system boundary, and time horizon differ (Levasseur et al., 2016; Peñaloza et al., 2019).

The management debate is consequently better understood as a set of conditional trade-offs than as a contest between universal rules. Production-oriented studies report large long-run benefits when higher growth supports sustained biomass supply and the additional wood displaces carbon-intensive products or fuels (Poudel et al., 2012; Lundmark et al., 2014; Gustavsson et al., 2021). Other studies find that increased harvest can worsen the greenhouse-gas balance over policy-relevant periods because reduced forest sequestration exceeds the avoided fossil emissions achieved through substitution (Hudiburg et al., 2019; Soimakallio et al., 2021; Skytt et al., 2021). Bioenergy illustrates this problem clearly: combustion releases carbon immediately, while biological repayment occurs later and only relative to a defensible forest counterfactual (Serman et al., 2018).

This review has four objectives: to clarify why forest-mitigation conclusions diverge across time horizons and accounting frameworks; synthesize evidence on conservation, production forestry, harvested wood products, material substitution, and bioenergy; identify assumptions that can overstate or understate benefits; and propose an integrative accounting framework. The central argument is that climate-optimal forestry cannot be reduced to harvest intensity alone. Decisions require explicit counterfactuals, time-aware metrics, full carbon accounting, and transparent tests of whether substitution is additional, durable, and large enough to compensate for forest-carbon opportunity costs.

2. Review Design and Evidence Boundaries

This article is a critical integrative review based on the supplied literature extraction rather than a new systematic search. The

evidence base contains 45 legacy records spanning 1996-2021 and one additional abstract used as a recent update. Twenty-three legacy records include abstracts, while the remainder provide bibliographic or contextual metadata. Because the corpus was supplied rather than generated through a reproducible multi-database protocol, the review is not presented as a systematic literature review or meta-analysis.

Claims were calibrated to evidence access. Study-specific methods, quantitative findings, causal interpretations, and limitations were drawn only from records containing abstracts. Metadata-only records were used conservatively for context or methodological lineage. The synthesis was organized around five recurring dimensions: ecosystem carbon, harvested wood-product storage, material and energy substitution, temporal climate response, and methodological choices involving baselines, system boundaries, and metrics. This thematic approach connects foundational accounting work (Schlamadinger & Marland, 1996; Werner et al., 2010) with national scenario studies and recent critical analyses (Harmon, 2019; Soimakallio et al., 2021; Skytt et al., 2021).

The review distinguishes source-reported findings from integrative interpretation. The four-ledger framework proposed later is a synthesis tool rather than a model tested in a single study. Its components are nevertheless grounded in recurring evidence on ecosystem stock changes, harvested-product pools, avoided fossil emissions, and timing-related opportunity costs.

3. Conceptual Architecture of Forest Climate Mitigation

Forest climate mitigation is best treated as a coupled biological-technological system. The biological subsystem determines carbon uptake, storage, mortality, decomposition, and disturbance, while the technological subsystem converts harvested biomass into products, buildings, energy, residues, and waste. Climate outcomes arise from the interaction of these subsystems.

Schlamadinger and Marland (1996) identified four core pathways: carbon storage in the biosphere, storage in forest products, displacement of fossil fuels by bioenergy, and displacement of emission-intensive materials by wood. Later forest-sector models retained this logic while representing product chains, trade, and management scenarios in greater detail (Werner et al., 2010; Smyth et al., 2017).

The first pathway is ecosystem sequestration. Forests remove carbon dioxide through photosynthesis and store carbon in living biomass, dead organic matter, and soils. Stock and flux are distinct: a forest with high standing carbon is not necessarily the forest with the highest annual sink. Forest age helps explain this difference, and global observations show that age strongly influences annual net ecosystem productivity (Besnard et al., 2018). Conservation studies likewise indicate that protected forests can maintain high carbon density while uptake varies with age, productivity, and disturbance (Sharma et al., 2013).

The second pathway is harvested wood-product storage. Harvest transfers part of ecosystem carbon into products whose residence times range from months to decades. Long-lived structural products can delay atmospheric return and may also replace more emission-intensive materials, whereas short-lived products provide limited storage. Product lifetime, cascading, end-of-life treatment, and replacement rates therefore affect the climate value of harvested carbon (Peñaloza et al., 2016; Peñaloza et al., 2019).

The third and fourth pathways are material and energy substitution. Avoided emissions can occur when wood genuinely replaces a higher-emission material or fossil fuel. However, displacement factors vary widely and depend on product function, manufacturing systems, energy sources, market behavior, and the forest supplying the wood (Sathre & O'Connor, 2010; Harmon, 2019). Bioenergy is even more time-sensitive because combustion releases carbon immediately while regrowth occurs

gradually. Dynamic analysis of wood replacing coal demonstrates that the timing of these flows can create multi-decadal carbon payback periods (Stermann et al., 2018).

These pathways are connected by opportunity cost. Carbon retained in a standing forest cannot simultaneously be embodied in a harvested product, and biomass used immediately for energy cannot simultaneously serve in a long-lived product. Increased harvesting can therefore improve

product or energy substitution while reducing ecosystem carbon relative to a lower-harvest baseline. The relevant climate quantity is the net atmospheric effect of all linked changes, not the gross benefit of one pathway (Hudiburg et al., 2019; Soimakallio et al., 2021). This leads to a constrained-optimization perspective in which carbon stocks, sink strength, product allocation, substitution quality, timing, disturbance, and ecological sustainability are evaluated together.

Table 1. Evidence architecture for evaluating forest-sector climate mitigation

Study context	Contrast	Analytical focus	Time scale	Key evidence	Ref.
Global forest-bioenergy systems	Protection, harvest, bioenergy, wood products	Biosphere, products, substitution	Long-term	Mitigation depends on productivity, land-use baseline, and biomass-use efficiency	Schlamadinger & Marland (1996)
Swiss forest and wood sector	Alternative management and wood-use pathways	Forest, products, energy recovery, trade	Long-term	Material and energy substitution can dominate product-stock effects, depending on boundaries	Werner et al. (2010)
Swedish intensive forestry	Reference vs. higher production	Linked forest, soil, and substitution models	100 years	Higher production can improve total balance when additional biomass is effectively substituted	Poudel et al. (2012)
Dynamic forest-product LCA	Short- and long-lived products under different baselines	Dynamic LCA	0-300 years	Time horizon, uptake timing, and baseline materially affect results	Peñaloza et al. (2019)
Wood bioenergy replacing coal	Coal vs. wood power	Dynamic carbon stock and flux model	Multi-decadal	Initial CO ₂ increase can create long payback periods	Stermann et al. (2018)
Finnish forest sector	Increased harvest vs. baseline	Forest sink, products, substitution	2015-2044	Increased harvest raised net GHG flow unless favorable conditions were met	Soimakallio et al. (2021)
Swedish productivity gradient	Harvest levels from no harvest to high harvest	Harvest, growth, substitution scenarios	30-50 years+	Reduced harvest improved near-term outcomes; long-term results depended on productivity and substitution	Skytt et al. (2021)

4. Temporal Trade-offs: Why the Time Horizon Can Reverse the Ranking of Strategies

Forestry has delayed causality. Harvest changes carbon stocks immediately, regrowth unfolds progressively, product carbon may remain stored for years or

decades, and substitution depends on technologies and markets that change over time. The same management action can therefore have one climate effect during the next several decades and another over a century. Time horizon should consequently be treated as a decision variable rather than a

neutral reporting convention (Levasseur et al., 2016; Peñaloza et al., 2019; Skytt et al., 2021).

Skytt et al. (2021) provides a clear recent illustration. Across Swedish counties with different productivity, reduced harvest increased climate benefits over short time scales of at least 50 years, while higher harvesting than the current level was counterproductive in the examined scenarios. Productivity affected both the magnitude and persistence of this benefit. Future substitution also mattered: if substitution effectiveness increases, higher harvest can become more competitive after mid-century in highly productive forests; if substitution weakens as non-wood industries decarbonize, lower-harvest strategies remain favorable for longer. This result shows why a fixed displacement factor is inadequate for long-term analysis (Harmon, 2019; Knauf et al., 2016).

Earlier Swedish studies reported a crossover under some conditions. Gustavsson et al. (2017) found that increased set-aside produced lower cumulative emissions than the reference case for roughly the first 90 years, after which reduced harvesting increased emissions from energy and material systems relative to production scenarios. Gustavsson et al. (2021) similarly found an initial period of about 30-35 years in which set-aside performed better before a high-production scenario generated stronger long-run mitigation. These results do not imply that crossover is inevitable. Soimakallio et al. (2021) found that increased Finnish harvest during 2015-2044 very likely raised net GHG flow because reduced forest sequestration exceeded avoided fossil emissions; more long-lived products, bioenergy with carbon capture and storage, and smaller forest-sink losses were identified as conditions that could improve the outcome.

Bioenergy reaches the same issue through carbon debt. Serman et al. (2018) modeled wood replacing coal and estimated 44-104 years for carbon-debt payback under the examined forest conditions after clearcut,

assuming the land remained forested. The significance is not that all bioenergy shares this payback time, but that combustion emissions and regrowth cannot be collapsed into instantaneous carbon neutrality. Dynamic building LCAs likewise show that forest growth, product lifetime, end-of-life treatment, and the integration horizon alter comparative outcomes (Peñaloza et al., 2016; Peñaloza et al., 2019).

Policy interpretation should therefore distinguish near-term atmospheric outcomes from distant cumulative endpoints. A 100- or 200-year benefit does not necessarily answer a 2030, 2040, or 2050 mitigation question. Conversely, an assessment limited to standing forest carbon can omit durable product storage and genuine displacement benefits. The most defensible practice is to report the full trajectory at multiple policy-relevant horizons, including cumulative impact and time to climate break-even.

5. Forest Management Intensity, Conservation, and the Meaning of “Additional” Biomass

The management debate contrasts two valid mechanisms. Conservation retains carbon in living forests and can strengthen the land sink, while production-oriented management can create repeated harvests whose products store carbon and displace fossil-intensive materials or energy. The key question is whether additional harvesting creates additional mitigation or simply reallocates carbon from an effective biological sink to a weaker product or energy pathway (Lundmark et al., 2014; Hudiburg et al., 2019; Skytt et al., 2021).

Production-oriented studies generally assume that forest growth or harvestable increment can increase without degrading long-term productivity. Poudel et al. (2012) reported a favorable total carbon balance when greater biomass production in north-central Sweden supported fossil-fuel and material substitution. Lundmark et al. (2014) likewise found that increased biomass production and substitution could expand forestry's mitigation contribution.

Gustavsson et al. (2017; 2021) showed that high-production scenarios can generate strong long-run benefits when additional biomass is used efficiently. These benefits arise from a chain of conditions: productivity must remain high, the extra biomass must be sustained, and product or energy use must generate durable displacement.

Conservation-oriented evidence highlights foregone sequestration. Hudiburg et al. (2019) found that historical wood-product use reduced the potential annual sink in western US forests, supporting attention to lower harvest, longer rotations, and more efficient wood use. Moomaw et al. (2020) similarly emphasized maintaining and increasing forest carbon removal alongside deep fossil-emission reductions. In Finland, Soimakallio et al. (2021) found that

additional harvest reduced forest sequestration enough to outweigh avoided fossil emissions over the study horizon. Thus, 'additional biomass' should mean biomass generated through sustainable additional growth, residues with lower opportunity cost, or improved utilization, not merely more wood removed from existing stocks.

A useful distinction is between harvest that mainly liquidates ecosystem carbon, harvest of residues or material likely to decompose relatively quickly, and harvest enabled by demonstrable sustainable productivity gains and directed to long-lived or high-substitution uses. These categories have different opportunity costs and should not receive identical climate treatment.

Table 2. Management strategies and climate performance across time horizons

Strategy	Near-term signal	Longer-term signal	Critical conditions	Decision use	Ref.
Reduced harvest	Retains ecosystem carbon and sink capacity	Benefit may persist or be overtaken	Productivity, disturbance, future substitution	Relevant when near-term atmospheric reduction is prioritized	Skytt et al. (2021)
Large set-aside	Can lower initial cumulative emissions	May be overtaken if foregone substitution grows	Energy mix, product use, displacement duration	Report crossover time, not only endpoint	Gustavsson et al. (2017; 2021)
Intensive production	Can reduce forest carbon initially	May generate larger cumulative benefit	Sustainable productivity, efficient use, durable substitution	Do not infer benefit from harvest volume alone	Poudel et al. (2012); Lundmark et al. (2014)
Increased harvest with weak substitution	Reduced sequestration can dominate	Outcome remains parameter-dependent	Product mix, forest sink response, displacement factor	Calculate the factor required to break even	Seppälä et al. (2019); Soimakallio et al. (2021)
Longer rotations/lower harvest	Preserves standing carbon and sink strength	May reduce wood available for substitution	Baseline demand and disturbance risk	Evaluate forest and product systems together	Hudiburg et al. (2019)

6. Material Substitution and the Problem of Displacement-Factor Transferability

Material substitution is influential because a wood product can avoid emissions when it replaces steel, concrete, plastic, or another higher-emission alternative. Yet replacement

is a counterfactual claim. The benefit depends on what would otherwise have been produced and consumed, so a displacement factor is a relationship between two product systems rather than a universal property of

timber (Sathre & O'Connor, 2010; Harmon, 2019; Leturcq, 2020).

Sathre and O'Connor (2010) reported wide variation across 21 international studies, with most displacement factors between 1.0 and 3.0 tC of avoided emissions per tC in wood product and a mean of 2.1. National estimates can be much lower. Smyth et al. (2017) reported consumption-weighted Canadian averages of about 0.54 for sawnwood and 0.45 tC tC-1 for panels, illustrating the influence of product mix and system boundaries. Seppälä et al. (2019) reframed the issue by estimating the factor required to compensate for increased harvest. Their Finnish scenarios required roughly 2.0-2.4 tC tC-1 under a 17-33% increase in domestic harvesting, compared with an estimated current average below 1.1. This

threshold approach directly links substitution to the forest-carbon cost of supplying additional wood.

Three further uncertainties are important. Harmon (2019) showed that long-run benefits can be overstated when analysts assume persistent displacement or favorable building and forest conditions. Leturcq (2020) emphasized market additionality: higher wood use does not guarantee lower production of the non-wood alternative. Finally, future decarbonization changes the counterfactual itself. Displacement against today's steel, cement, electricity, or fuels may not remain valid for future decades (Knauf et al., 2016; Skytt et al., 2021). Substitution analysis should therefore specify the displaced product, factor, duration, additionality, and time path.

Table 3. Evidence on displacement factors and substitution assumptions

Application	Metric	Reported result	Main uncertainty	Implication	Ref.
International wood products	Meta-analysis across 21 studies	Most values 1.0-3.0; mean 2.1 tC/tC	Products and assumptions	Benchmark, not universal coefficient	Sathre & O'Connor (2010)
Canadian product mix	Consumption-weighted factors	~0.54 sawnwood; ~0.45 panels	National product mix	System averages can be far below selected cases	Smyth et al. (2017)
Finnish increased harvest	Required displacement factor	~2.0-2.4 required; current average <1.1	Forest sink and product mix	Compare expected with required displacement	Seppälä et al. (2019)
Building products	Sensitivity analysis	Some long-run benefits may be overestimated	Persistence and forest counterfactual	Test factor duration and forest response	Harmon (2019)
Economy-wide substitution	Additionality critique	More wood use need not reduce non-wood output	Market growth	Separate engineering from market substitution	Leturcq (2020)

7. Harvested Wood Products, Buildings, and Carbon Storage

Harvested wood products occupy an intermediate position between forests and the industrial economy. They are neither permanent sinks nor immediate emissions. Their climate contribution depends on residence time, the service provided while carbon is stored, the displaced alternative, and end-of-life treatment. Buildings are especially relevant because structural wood can retain carbon for decades while replacing

materials with high process emissions (Peñaloza et al., 2016; Smyth et al., 2017; Peñaloza et al., 2019).

Dynamic LCA shows why storage must be temporally qualified. Peñaloza et al. (2016) found lower climate impacts with greater biobased material use in the building scenarios examined, but the magnitude varied with service life, end-of-life treatment, forest growth or regrowth timing, and the assessment horizon. Chen et al. (2014) similarly demonstrated at national

scale that harvested products can contribute through both carbon storage and avoided fossil emissions, while future forest-stock trajectories remain important to the net balance.

Cascade use can strengthen the product pathway by using wood first in material applications, then reusing or recycling it where feasible, and directing residual or end-of-life wood to energy recovery (Werner et al., 2010). This sequence extends carbon residence time and preserves the possibility of material substitution before combustion. Soimakallio et al. (2021) identified a greater share of long-lived wood products as one condition that could improve the climate case for increased harvest. The strongest policy case is therefore not that wood stores carbon in isolation, but that sustainably supplied wood can store carbon for a meaningful period, genuinely displace higher-emission materials, and enter circular or cascading pathways.

8. Forest Bioenergy: Carbon Neutrality, Carbon Debt, and Feedstock Quality

Forest bioenergy is highly contested because combustion releases biogenic carbon dioxide immediately, while climate benefit depends on later regrowth and avoided fossil emissions. Treating biomass as zero emissions at the point of combustion hides the timing, forest opportunity cost, and supply-chain processes that determine the net atmospheric effect (Sterman et al., 2018; Moomaw et al., 2020; Leturcq, 2020).

Sterman et al. (2018) showed the importance of this dynamic accounting. In their wood-for-coal scenario, lower combustion and processing efficiency for wood created an immediate increase in atmospheric carbon dioxide. Regrowth gradually repaid the debt, but estimated payback ranged from 44 to 104 years depending on forest type. The relevant lesson is not a universal payback value; it is that bioenergy performance depends on the sequence of emissions and removals relative to a counterfactual.

Feedstock origin is decisive. Harvesting a living tree that would otherwise remain

stored and continue sequestering carbon carries a larger opportunity cost than using some residues or waste wood that would otherwise decompose or be burned without energy recovery. Gustavsson et al. (2017) reported additional benefits from residue recovery within a broader productive system. Residues are not impact-free because they can contribute to soil carbon and nutrient cycling, but they should be distinguished from additional roundwood harvested solely for combustion. The displaced energy source also matters: bioenergy yields larger avoided emissions when replacing high-emission fuels, but the benefit can shrink as electricity and heat systems decarbonize (Smyth et al., 2017; Knauf et al., 2016; Skytt et al., 2021). Conversion efficiency, harvesting, transport, processing, and drying should be included in the same accounting boundary. Integrated systems can improve performance by prioritizing material uses and using residues or end-of-life wood for energy (Werner et al., 2010). Carbon capture and storage could further alter the ledger, as noted by Soimakallio et al. (2021), although the supplied corpus does not support a detailed assessment of deployment feasibility. Overall, the strongest scrutiny is warranted for additional harvest of high-carbon, slow-recovering biomass for immediate combustion; lower-opportunity-cost feedstocks become more plausible when used efficiently to displace high-emission fossil energy and when break-even occurs within the relevant policy horizon.

9. Forest Age, Productivity, Disturbance, and Biological Constraints

Carbon accounting can become unrealistic if forest productivity is treated as fixed. Productivity changes with age, site conditions, climate, nutrient status, disturbance, and management, affecting both ecosystem sequestration and the biomass available for substitution. Besnard et al. (2018), using observations from 126 forest eddy-covariance sites, found forest age to be a major factor explaining annual net ecosystem productivity. This distinction

matters because policies that maximize annual increment can favor younger stands, while policies that preserve standing carbon can favor older stands; neither metric alone represents the full climate balance.

Disturbance complicates this relationship. Sharma et al. (2013) found that protected Canadian forests generally held greater carbon density than surrounding managed references, while uptake varied with forest age, productivity, and disturbance history. Conservation scenarios should therefore not assume static old forests, just as production scenarios should not assume uninterrupted regrowth. Site productivity also affects how rapidly carbon debt can be repaid and how much biomass can be supplied without eroding long-term stocks (Schlamadinger & Marland, 1996; Skytt et al., 2021).

Forest health adds another constraint. Piri and Valkonen (2013) documented the spread of *Heterobasidion* root rot in uneven-aged Norway spruce stands, illustrating a mechanism through which management structure can affect future timber quality and productivity. Although the study did not quantify carbon effects, it reinforces the need for sensitivity analysis where long-run mitigation depends on sustained yields. Carbon optimization should also remain within ecological limits: biodiversity, soil function, and resilience are components of sustainable forest management and can influence the durability of future carbon benefits (Werner et al., 2010).

10. Baselines, System Boundaries, Metrics, and the Architecture of Accounting

Many disagreements in forest-climate assessment arise from accounting architecture rather than from different physical processes. Three choices are especially influential: the baseline against which change is measured, the spatial and sectoral boundary, and the climate metric

used to aggregate emissions through time (Levasseur et al., 2016; Peñaloza et al., 2019).

The baseline defines additionality. A no-harvest baseline assigns an opportunity cost equal to the difference between harvested and protected forest trajectories, while a business-as-usual baseline counts only changes relative to current management. Different regeneration or management baselines can therefore change the magnitude or even the sign of a modeled benefit without changing the physical intervention. System boundaries create a parallel problem. Stand-level analysis captures local stock change but can miss downstream substitution; national analysis includes forest industries but may misallocate exported effects; broader boundaries better represent trade but require more assumptions. Werner et al. (2010) and Lundmark et al. (2014) illustrate why territorial inventories and global product-system effects should be distinguished.

Climate metrics impose a temporal value system because near-term and delayed forcing are weighted differently. Dynamic approaches preserve the timing of biogenic emissions and removals that static characterization can obscure. Robust studies also use sensitivity or threshold analysis rather than presenting a single deterministic scenario. Soimakallio et al. (2021) used stochastic simulation; Seppälä et al. (2019) calculated a required displacement factor; and Skytt et al. (2021) varied harvest levels, productivity, and future substitution. These approaches identify how large a parameter change must be before a conclusion changes. High-quality assessment should also keep stocks and flows distinct. Forest carbon stock, annual sequestration, harvested-product stock, annual product inflow, and avoided fossil emissions are different quantities. Transparent ledgers make the drivers of each result visible and reduce the risk of double counting.

Table 4. Minimum methodological specifications for credible forest-climate assessment

Dimension	Minimum specification	Why it matters	Common failure	Sensitivity test	Ref.
Baseline	Explicit no-harvest, BAU, intensified, or regeneration counterfactual	Mitigation exists only relative to an alternative future	Ignoring the alternative forest trajectory	Recalculate against at least two defensible baselines	Peñaloza et al. (2019)
Time horizon	Report policy-relevant and long-run horizons	Emissions, regrowth, and product turnover are asynchronous	Only reporting a distant endpoint	Show trajectory and break-even year	Levasseur et al. (2016); Skytt et al. (2021)
Forest carbon	Include stock change and foregone sequestration	Harvest changes stocks and future sink strength	Assuming biomass is carbon neutral at harvest	Vary growth, age, and rotation	Besnard et al. (2018); Sterman et al. (2018)
Product carbon	Specify lifetime, cascading, and end-of-life	Storage benefit depends on residence time	Treating HWP storage as permanent	Test service-life distributions	Peñaloza et al. (2016)
Substitution	Specify displaced product, factor, duration, additionality	Avoided emissions are counterfactual and time-varying	Applying a universal factor indefinitely	Use low/central/high and time-varying factors	Harmon (2019); Seppälä et al. (2019)
Bioenergy	Identify feedstock, efficiency, and displaced fuel	Whole trees, residues, and waste have different opportunity costs	Zero-rating stack CO ₂	Calculate debt and payback by feedstock	Sterman et al. (2018); Smyth et al. (2017)
Uncertainty	Quantify parameter and scenario uncertainty	Rankings can be conditional	Single deterministic scenario	Stochastic or threshold analysis	Soimakallio et al. (2021)

11. An Integrative Four-Ledger Framework for Decision-Making

The evidence supports an integrative framework with four linked ledgers. Ledger 1 is ecosystem carbon: differences in living biomass, dead organic matter, soil carbon, and net ecosystem exchange between intervention and baseline trajectories. Ledger 2 is harvested-product carbon: transfers into products, residence times, cascading pathways, and end-of-life emissions. Ledger 3 records verified avoided fossil and process emissions from material or energy substitution. Ledger 4 captures temporal opportunity costs, including foregone sequestration, delayed regrowth, and the atmospheric consequence of when emissions and removals occur. These components recur across forest-system models, LCA studies, and national carbon assessments (Schlamadinger & Marland, 1996; Werner et al., 2010; Moomaw et al., 2020).

The framework prevents a strong result in one pathway from masking losses in another. A high displacement factor does not establish net benefit if ecosystem carbon declines more; a large harvested-product pool is not permanent if end-of-life emissions occur within the horizon; and a favorable long-run balance can still carry a near-term penalty if atmospheric carbon remains elevated for decades (Sterman et al., 2018; Peñaloza et al., 2019; Skytt et al., 2021).

Two decision metrics improve comparability. Time to climate break-even identifies when cumulative impact becomes lower than the specified baseline. The required displacement factor asks how much avoided fossil emission is needed for additional harvest to compensate for ecosystem and product-carbon changes. Together, these metrics explain why no single harvest intensity is universally optimal: outcomes depend on existing carbon

stocks, productivity, product allocation, substitution effectiveness, and the policy horizon (Seppälä et al., 2019; Gustavsson et al., 2021).

12. Implications for Climate and Forest Policy

Forest policy should complement, not substitute for, deep fossil-emission reductions. High-carbon stocks and strong sinks warrant protection where harvesting would create long break-even periods, while production strategies are more defensible where sustainable growth, long-lived products, and verifiable displacement generate robust benefits (Moomaw et al., 2020; Hudiburg et al., 2019). Spatial differentiation is appropriate because productivity, age structure, disturbance, and product systems vary among forests (Sharma et al., 2013; Besnard et al., 2018; Skytt et al., 2021).

Industrial policy should prioritize long-lived, reusable, and cascading material applications before energy recovery where feasible. Residues and waste wood can retain an energy role when they displace high-emission fuels and have favorable ecological counterfactuals (Werner et al., 2010; Peñaloza et al., 2016; Smyth et al., 2017). Reporting should also distinguish territorial inventory effects from global product-system effects so that exported products and downstream emissions are allocated transparently (Lundmark et al., 2014; Hudiburg et al., 2019).

13. Research Priorities for the Next Generation of Forest-Climate Reviews and Models

Future research should first replace fixed substitution coefficients with dynamic counterfactuals linked to plausible decarbonization of steel, cement, electricity, and heat. Market additionality should be tested so that engineering substitution is not automatically equated with economy-wide displacement (Knauf et al., 2016; Harmon, 2019; Leturcq, 2020; Skytt et al., 2021).

Second, uncertainty analysis should jointly represent forest growth, age structure, disturbance, product lifetime, energy mix, and substitution. Stochastic and threshold approaches are especially important where long-run benefits depend on sustained high productivity (Besnard et al., 2018; Soimakallio et al., 2021). Third, studies should publish annual or decadal climate trajectories, break-even time, and results at multiple horizons rather than only distant endpoints (Levasseur et al., 2016; Peñaloza et al., 2019).

Finally, climate optimization should be linked more explicitly with ecological resilience and portfolio design. Disease, soil condition, disturbance, and biodiversity can affect future biomass supply and carbon permanence (Piri & Valkonen, 2013; Werner et al., 2010). Landscape-scale portfolios combining conservation, production forests, longer rotations, efficient material use, residue-based energy, reuse, and recycling may be more robust than uniform high- or low-harvest strategies.

14. CONCLUSIONS

Forest climate mitigation is a dynamic allocation problem across ecosystems, products, energy systems, and time. The evidence does not support a universal rule that either greater harvesting or greater conservation is always superior. Lower harvest generally strengthens near-term ecosystem carbon retention, particularly where standing stocks are high and substitution benefits are modest or declining. Production-oriented strategies can become more competitive over longer horizons when sustainable productivity is genuinely increased, wood is directed to long-lived uses, and high-emission materials or fuels are demonstrably displaced (Gustavsson et al., 2021; Skytt et al., 2021).

The strongest methodological lesson is that baselines, boundaries, and timing shape conclusions. Static carbon-neutrality assumptions, universal displacement factors, and distant endpoints can hide substantial near-term costs, while forest-only accounting

can omit product storage and real fossil-emission displacement (Harmon, 2019; Sterman et al., 2018; Smyth et al., 2017). The proposed four-ledger framework integrates ecosystem carbon, harvested-product storage, avoided emissions, and temporal opportunity costs. Used with break-even time and required displacement factor, it provides a transparent basis for comparing management strategies without privileging one carbon pathway in advance.

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