Closing the carbon removal attribution gap requires an objective atmospheric basis

Alexandra J. Ringsby[1]* , Marc N. Roston[2], Gian M. Mallarino[3], Mislav Radic[3], and Kate Maher[4]

[1]Department of Chemical Engineering, Stanford University, Stanford, CA 94305, United States
[2]Sustainable Finance Initiative, Stanford University, Stanford, CA 94305, United States
[3]Department of Social and Political Sciences, Bocconi University, 20136 Milan, Italy
[4]Department of Earth System Science, Stanford University, Stanford, CA 94305, United States

*Correspondence to: aringsby@stanford.edu

Science for Society

Achieving the goals of the Paris Agreement depends not only on deploying carbon dioxide removal (CDR), but on the accounting infrastructure used to define and track its climate impact. Today, removals are increasingly credited through project-based markets that operate independently from other systems and without explicit linkages to the atmospheric carbon balance. This decoupling risks an "attribution gap," where credited removals coexist with uncounted emissions, potentially distorting international climate targets and weakening incentives to decarbonize hard-to-abate sectors.

We introduce an Objective Atmospheric Basis (OAB): a shared accounting infrastructure that tracks emissions and removals using physical carbon balances and two-column environmental ledgers. Rather than defining policy outcomes, OAB provides a neutral data interpretation layer that can be used across carbon markets, national inventories, and Article 6 cooperation mechanisms. Applied to biochar carbon removal, it shows that upstream emissions can determine whether a project delivers net removal or emissions reductions. Integrating this accounting layer with net-zero target design, crediting rules under Article 6, and economic incentives for industry could help ensure that carbon markets complement—but not replace—direct emissions reductions, while avoiding atmospheric debt shifting.

Highlights

- Current carbon removal accounting infrastructure creates attribution gaps, where removals are credited while associated emissions remain in the atmosphere.
- We introduce an Objective Atmospheric Basis (OAB) that tracks carbon explicitly using mass balance, treating emissions as persistent liabilities and removals as assets.

- Applying OAB to biochar shows that upstream emissions allocation often determines net climate impact, with some residue-based systems shifting emissions burdens rather than delivering removals.
- OAB functions as accounting infrastructure that enables consistent interpretation of carbon fluxes across projects, national inventories, and Paris Agreement Article 6 mechanisms.

Summary

Efforts to integrate carbon dioxide removal (CDR) into climate policy, markets, and inventories are advancing rapidly, but without a unified accounting logic to attribute atmospheric impacts. Existing crediting approaches omit upstream emissions, creating a structural *attribution gap* in which removals are credited even as associated emissions remain in the atmosphere. Although it remains small today, we find that this gap could reach gigaton-scale annually in biomass-based CDR systems. To address this discrepancy, we propose an Objective Atmospheric Basis (OAB): a technology-agnostic accounting framework that tracks carbon transfers explicitly using mass-balance ledger that casts emissions as persistent liabilities and removals as assets. Applied to feedstock materials for biochar carbon removal (BCR), OAB reveals how system boundaries and emissions allocation decisions shape net removal outcomes. By reconciling emissions and removals within a single atmospheric reference frame, OAB closes the attribution gap and provides core infrastructure for scalable, high-integrity CDR. As a common language for carbon bookkeeping grounded in physical fluxes, OAB enables consistent crediting across jurisdictions, supports policy decision-making, and strengthens alignment between Article 6 implementation and global temperature goals.

Introduction

Limiting warming to 1.5°C will require 100–300 $GtCO_2e$ of cumulative carbon dioxide removal (CDR) by 2100, an ambition grounded in science-based net-zero targets[1,2] and codified in the Paris Agreement.[3,4] Article 6 of the Agreement establishes a framework for international cooperation, enabling countries to meet their nationally determined contributions (NDCs) through bilateral trading (Article 6.2) and a centralized crediting mechanism (Article 6.4). To date, 78% of countries anticipate using these mechanisms, with CDR expected to contribute up to 3.5 $GtCO_2e$ by 2030.[5,6]

Yet the climate impact of these pledges will depend not only on the volume of removal credits delivered, but also on the quality of the accounting infrastructure that defines, verifies, and transfers atmospheric mitigation outcomes.[7,8] Current systems credit removals without a direct linkage to the atmospheric carbon balance, enabling crediting outcomes to drift from the physical carbon flows they are meant to represent—a structural divergence we term the *attribution gap*. As CDR scales, this gap could propagate across international market systems, eroding the atmospheric integrity of the Paris framework and undermining global efforts to fight climate change.[9]

Historical experience illustrates how accounting infrastructure can shape the relationship between credited and atmospheric impact. Under the Clean Development Mechanism (CDM)—a system built to facilitate cost-effective emissions reductions and avoidances—credit issuance relies on unverifiable additionality tests, arbitrary baselines, and flexible system boundaries. Although CDM methodologies have evolved, accounting reflects modeled scenarios rather than realized atmospheric impacts:[10–14] despite more than $400 billion invested,[15] a recent systematic review found that fewer than 16% of examined offset credits minted under the CDM and other programs delivered real emission reductions.[16] This experience demonstrates a broader structural lesson: without a clear reference frame anchored to the atmospheric carbon balance, accounting architectures cannot guarantee alignment between credited and physical outcomes.

Contemporary CDR crediting systems risk repeating this structural flaw. Many programs retain project-based architectures developed for emissions avoidance,[17–22] even as removals are expected to scale far beyond historical markets and perform distinct functions in net-zero pathways.[23,24] Additionality tests and counterfactual logic—intrinsic to emissions avoidance and reduction schemes[25]—sit uneasily with removals, which can in principle be quantified directly through observable carbon fluxes. Jurisdictional and programmatic fragmentation further embeds incompatible system boundaries and normative choices into core accounting rules.[21,22,26,27] Together, these features impede comparability across contexts and obscure what constitutes atmospheric CO_2 removal,[2,28–36] creating and widening the attribution gap as CDR scales.

Addressing the attribution gap requires a foundational reference frame that consistently links project-level data to the atmospheric carbon mass balance. We propose an objective atmospheric basis (OAB) for CDR accounting: a physically grounded accounting layer that records carbon fluxes using a ledger-based architecture analogous to financial accounting (Box 1). Under OAB, positive greenhouse gas (GHG) fluxes (emissions) and negative fluxes (removals) are treated as additive inverse liability-asset pairs traced across process stages. This structure separates objective, measurement-based accounting from normative crediting decisions, enabling regulators, crediting programs, and market participants to apply different governance choices without obscuring underlying atmospheric impacts. By providing a consistent foundation on which disparate actors and policies can operate, OAB links empirical carbon data to transparent, interoperable decision frameworks and provides a pathway toward convergent accounting under Article 6.

In the sections that follow, we situate OAB within the evolution of carbon accounting architectures and apply it to biochar carbon removal (BCR), a dominant pathway in today's engineered CDR portfolio. We then evaluate how an OAB architecture could prevent attribution gaps, balance mitigation incentives, and strengthen the implementation of Article 6.

Box 1: Accounting for removals with an Objective Atmospheric Basis

An effective carbon removal accounting infrastructure should use an environmental ledger to track atmospheric carbon flux, apply consistent and fair allocation rules, and apply equally across all CDR pathways:

(1) **Anchor in atmospheric mass balance:** All system boundaries are defined relative to atmospheric carbon. Only with an atmospheric reference frame can atmospheric removal be inferred.

(2) **Consistently allocate upstream emissions:** Ensure consistent allocation of upstream emissions in multifunctional systems using a distribution coefficient, q^*, that assigns burdens across co-products.

(3) **Track carbon explicitly:** Record carbon flux as a physical transfer using environmental ledgers.

(4) **Track emissions and removals as durable ledger entries:** Adopt a technology and policy-agnostic representation of carbon fluxes across the whole process value chain. Assets and liabilities represent additive inverse pairs.

(5) **Enable dynamic permanence tracking:** Perform liability retention and rebalancing when storage is lost or degraded. Require re-evaluation of storage inventories at appropriate intervals.

Evolution and Limitations of Carbon Accounting Architectures

As Article 6 links accounting systems across contexts and scales, inconsistencies among them magnify risks of misrepresentation and create administrative barriers to international trade.[23,37,38] Project-level crediting approaches remain methodologically fragmented and often fail to distinguish emissions reductions from removals,[27,32,39–42] rendering them poorly aligned with jurisdictional and national frameworks. Those higher-level systems likewise rely on additionality tests and baseline logic but typically operate on aggregated observational data with limited project-level specificity.[3,37] At the planetary scale, integrated assessment and Earth system models represent mitigation explicitly as physical carbon flows.[3,43] These layers cannot converge without a unifying reference frame; just as financial accounting depends on standardized rules to ensure interoperability, carbon accounting must function as a shared infrastructure across scales.[2,42,44,45] Nested architectures, where project data aggregates cleanly into jurisdictional and global assessments, are only feasible if all scales draw on neutrally defined flux units.[38]

A common, interoperable basis linking project-level carbon fluxes to atmospheric outcomes provides this neutral foundation.[3,43] Carbon accounting now spans diverse institutions and objectives—from project crediting to policymaking and national inventory management. While different objectives may necessitate different *interpretations*,[26,27,46] the *practice* of accounting should consistently represent material carbon flows. Flux-based accounting accomplishes this by selecting and interpreting the subset of observable greenhouse gas flows attributable to a CDR project[10] Life cycle assessment (LCA) has formalized such logic through "cradle-to-grave" inventories, yet LCA was not designed for CDR and leaves wide discretion over system boundaries, treatment of multi-functional processes, and the classification of emissions reductions versus removals.[10,39,47,48] Standards that permit "zero-burden" treatment (i.e., no upstream emissions allocation) of "waste" feedstocks further distort flux logic and undermine efforts to distinguish emissions reductions from true CDR[10,49–55].

These inconsistencies are especially acute in biomass-based systems, which sit at the intersection of LCA conventions, feedstock classifications, and upstream allocation. A recent review of 36 distinct biochar deployments found that project impacts determined with LCA methods could not be reliably intercompared due to inconsistent boundary conditions, functional units, and other parameters.[56] At roughly 1 tCO_2e of embodied emissions per tonne of biomass carbon produced,[57–59] full mobilization of sustainably harvestable crop residues in such systems without proper attribution could bias global CDR balances by nearly 1.4 $GtCO_2e$ annually.[60] Such distortions illustrate how inconsistencies in accounting infrastructure—rather than performance of individual CDR pathways—can propagate substantial attribution gaps at scale.

Analytical framework and allocation methodology

A carbon accounting architecture capable of preventing attribution gaps should operate from a common atmospheric reference frame and represent both mitigation and ownership through empirically grounded carbon transfers. OAB meets these requirements by tracking carbon explicitly through mass-balance principles implemented in a two-column ledger system. To illustrate how OAB links physical fluxes to ownership and liability, we apply the framework to a gradient of biomass-based systems—from pristine ecosystems to intensively managed croplands and biochar production—and show how the architecture preserves causal correspondence between carbon flows and CDR claims.

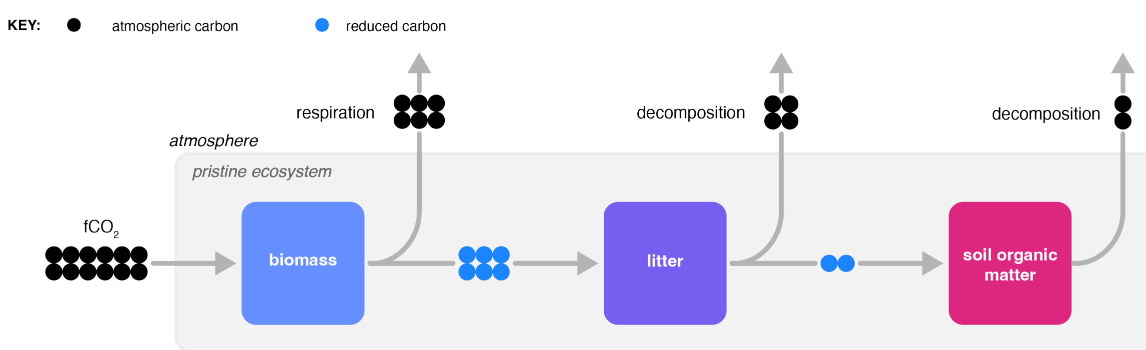


Figure 1: Molar flux of carbon in pristine ecosystems, where the influx of atmospheric carbon (fCO_2) is in balance with efflux of carbon via soil respiration from roots and heterotrophic organisms. Note that half of the influx of carbon from the atmosphere is immediately respired by plants such that photosynthesis is roughly 50% efficient.[62] Decomposition from successively slower-cycling pools (i.e., litter, soil organic matter) balances the remaining carbon to yield a system at equilibrium.

Pristine and unmanaged ecosystems

Pristine, undisturbed, and unmanaged ecosystems define the null removal case. Although they exchange carbon continuously with the atmosphere, their carbon inventory remains nominally at steady-state: atmospheric carbon uptake by plant biomass (fCO_2) is balanced by biogenic carbon emissions from soil respiration and decomposition.[61] This equilibrium yields a constant ecosystem carbon reservoir ($C(t)$) with no net carbon storage over time (Fig. 1).

Under OAB, carbon removed from the atmosphere and stored in a reservoir is designated as an asset, while any subsequent release of oxidized carbon back to the atmosphere constitutes a liability. Systems at steady-state generate neither assets nor liabilities, indicated by a storage rate of zero,

$$\frac{dC}{dt} = \dot{C}_{\text{in}} - kC = 0 \tag{1}$$

where $\dot{C}_{\text{in}}$ is the mass flux of carbon into the system and k is the system loss coefficient. Although these ecosystems may display substantial carbon stocks ($C(t) >> 0$) and fluxes, mass accumulation may have occurred long ago, constituting no additional removal. Accordingly, fluxes in these systems are not creditable.

Some pristine ecosystems may temporarily accrue carbon (i.e., $dC/dt > 0$) due to CO_2 fertilization, enhanced precipitation, or temperature changes associated with climate change.[43] However, these are unmanaged and potentially non-durable gains—and should not be recognized as removals on an environmental ledger without additional intervention and assumed oversight.[45] Including passive sinks in net-zero claims also obscures national inventory and target setting, thereby undermining climate change mitigation objectives.[3,43,63]

While pristine ecosystems cannot generate new carbon assets, they can still incur liabilities. Storage reversal can occur in response to wildfire, drought, pestilence, deforestation, and other disturbances.[64,65] When such reversals occur, the landowner—private or public—must recognize a carbon liability even in the absence of a prior carbon asset or credited removal.[45]

Managed ecosystems

In contrast to pristine ecosystems, managed ecosystems and croplands introduce intentional and deliberate intervention that disrupts the carbon balance, creating measurable departures from equilibrium that enable assets and liabilities to be established (Fig. 2). Carbon fluxes here encompass both biological processes, including non-CO_2 GHGs (e.g., N_2O and CH_4), and emissions resulting from material inputs (e.g., seedling production and planting, fertilizer usage, tillage, harvesting).[66] Under OAB, these systems are modeled with the following dynamic mass balance:

$$\frac{dC}{dt} = \sum_i A_i - \sum_j L_j = \sum_i A_i - kC - \sum_j E_j \tag{2}$$

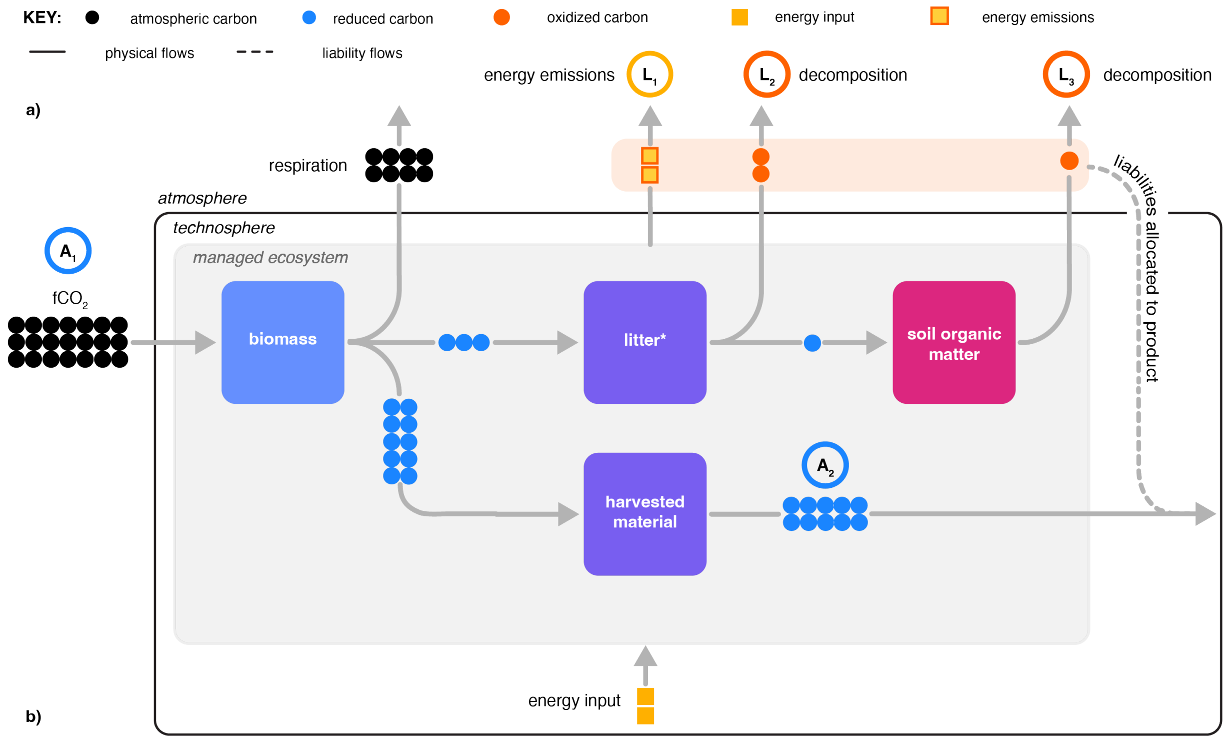
where $\sum_i A_i$ represents the carbon added to storage as assets, and $\sum_j L_j$ is the sum of liability fluxes resulting from system feedbacks (kC) and technospheric emissions ($\sum E_j$). Although system energy inputs are not directly tracked as liabilities, the associated emissions (E_j) are. Under this framework, carbon assets (A_i) can be generated and transferred, while liabilities persist and must be rebalanced if storage degrades. In principle, these systems may also inherit upstream liabilities from infrastructure establishment and raw material production. For simplicity, these liabilities are not considered here.

The resulting environmental ledger (Fig. 2b) links the biophysical mass balance (Fig. 2b) to ownership transfers: photosynthesis generates assets, in-system emissions create liabilities, and both are assigned to harvested biomass at the point of sale.[44] Each subsequent transaction carries its carbon value with it to enable traceable responsibility through the supply chain.

The OAB framework thus achieves two objectives:

1. **Accountability:** the land manager's closing balance, and
2. **Asset quantification:** the atmospheric mass balance over the reporting period.

Here, a closing balance of zero implies neither additional carbon liability nor remaining transferable assets. The value of assets passed downstream depends on the removal value of



b)

Assets	Removal Units	Liabilities	Emission Units
Assets directly produced through operations	10	Liabilities directly produced through operations	5
A1 *CO_2 fixed in biomass*	*13*	L1 *cultivation and harvest emissions*	*2*
Impairment of generated assets	*(3)*	L2 *decomposition emissions*	*2*
		L3 *decomposition emissions*	*1*
Subtract assets transferred to customers A2	(10)	Subtract liabilities transferred to customers	(5)
Closing assets	0	**Closing liabilities**	0

Figure 2: a) Semiquantitative representation of carbon flows in managed agricultural systems, where the influx (fCO_2) and efflux (respiration and decomposition flux) of carbon may no longer balance. Some CO_2 influx is immediately respired due to photosynthetic inefficiency (black dots denoted respiration).[62] The system boundary (gray box) includes technospheric energy inputs (e.g., machinery, water pumping, and fertilizer). Litter* denotes residues left on field per sustainable harvest guidelines.[67] **b)** The associated environmental balance sheet: photosynthesis generates assets; in-system GHG and energy-use emissions create liabilities. Assets/liabilities tied to products transfer to end-users at sale (indicated with parentheses). Flows follow a sign convention (in = positive, out = negative) with fictious, dimensionless units. Supplier liabilities (e.g., liabilities associated with fuel, seeds, equipment) are omitted for simplicity.

captured carbon relative to ancillary emissions. While this system mirrors the presentation of E-assets under the E-liability framework,[45] OAB treats assets as physical fluxes from the atmosphere to storage without prescribing what constitutes a tradable unit. Under OAB, asset/liability matching provides a critical test of carbon accountability, with the mass balance as the central arbiter of integrity according to the process emissions inventory. Managed systems thus mark the first point where human intervention transforms flux assessment into verifiable climate accountability, a necessary bridge between biophysical realities and market governance.

Biochar systems

BCR (>80% of historic engineered carbon removal deliveries[68]) commonly utilizes crop residues derived from food systems. Under zero-burden accounting rules, cultivation-phase emissions in food systems are attributed exclusively to primary food products. Residues enter the biochar production gate burden-free (e.g., Fig. 2, L_1, L_2, L_3) despite their material connection to the biomass.[51,55,69–71] Upscaled to biochar carbon removal (BCR) systems, OAB addresses this distortion via rule-based allocation to restore the causal link between emissions investment and project-level climate service.

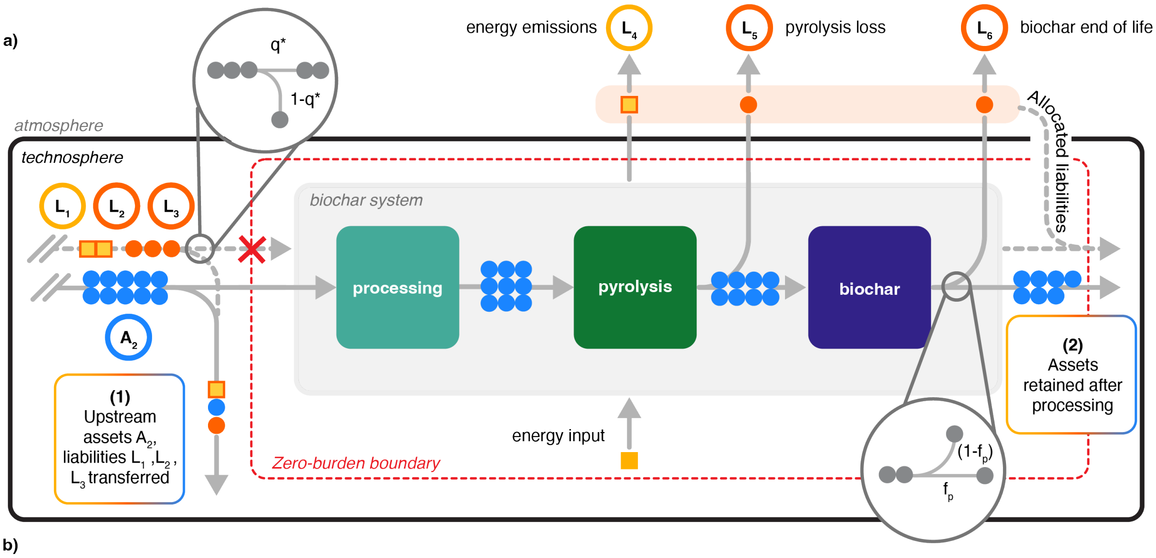
Allocation across co-products

Allocation is the critical step in determining how carbon accountability propagates through a value chain to result in a system-wide carbon budget. First, OAB tracks and transfers ledger items from the land manager to the biochar producer. Upstream liabilities are then partitioned and carried forward, defining clear system boundaries and ensuring net-zero aligned process emissions assessments (see OAB versus zero-burden inventory in Figure 3**a**).

In practice, once feedstock enters the BCR system, upstream emissions are allocated to update the biochar producer's environmental ledger, reflecting both net process emissions and carbon ownership. Net-negativity depends on whether the carbon storage value of the feedstock exceeds operational and inherited emissions liabilities (Fig. 3**b**) The closing balance shows the net position of asset and liability fluxes, yielding one of three possible outcomes: *(1)* assets exceed liabilities, resulting in a transferable asset, *(2)* assets match liabilities resulting in no outstanding obligations, but no potential removal benefit, or *(3)* liabilities exceed assets, leaving the producer with outstanding obligations and no viable removal assets.

Unlike economic allocation, which links emissions to fluctuating market prices, or "zero-burden" assumptions that admit low-value co-products burden free, OAB introduces a distribution coefficient (q^*) to allocate embodied emissions in proportion to carbon content. For example, if an agricultural producer yields primary and secondary biomass products in equal mass ratio and carbon content, each stream receives 50% of the production emissions (see the supplementary information (SI) for methods). This carbon-based method prevents opportunistic partitioning and ensures that even low-value co-products inherit an appropriate share of upstream process emissions. In doing so, OAB ensures that allocation is proportional to a product's removal value and reflective of the embedded energy and carbon necessary to produce it. This strategy establishes parity across pathways and projects—and is an essential element of OAB as a consistent, interoperable accounting architecture.

a)



b)

Assets	Removal Units	Liabilities	Emission Units
Add assets acquired from suppliers	9	Add liabilities acquired from suppliers	3
A_2 *CO_2 fixed in biomass*	*10*	q* × L_1 *cultivation and harvest emissions*	*1*
units sold to food/industry	*(1)*	q* × L_2 *decomposition emissions*	*1*
Impairment of purchased assets	(2)	q* × L_3 *decomposition emissions*	*1*
		Liabilities directly produced through operations	3
		L_4 *processing and production emissions*	*1*
		L_5 *pyrolysis loss*	*1*
		L_6 *decomposition emissions*	*1*
Closing assets	7	**Closing liabilities**	6

Figure 3: a) Carbon fluxes in biochar systems, with **(1)** upstream assets and liabilities transferred from residue producer (see Fig. 2) to storage operator at purchase according to the emissions partition coefficient ($q*$). The red dashed "zero burden" boundary excludes upstream liabilities L_1, L_2, and L_3. Biochar production adds new liabilities but yields net assets that can be sold or retained by the removal operator. Based on current market treatments, biochar's quality determines its permanence factor (f_p), which defines the fraction of carbon expected to remain over 100 years.[72,73] Alternative time-dependent formulations are compatible with the objective atmospheric basis (OAB) to determine the resulting outflow of reduced carbon units **(2)**. See symbol key in Figure 2. **b)** The associated environmental balance sheet: assets from photosynthesis and liabilities generated from upstream processes and biochar pyrolysis. Net removal occurs when assets exceed liabilities.

Upstream burdens determine atmospheric carbon removal

OAB dictates that a CDR claim is valid only when it reflects net atmospheric removal, not merely carbon storage within a project boundary. Applying OAB allocation to three representative BCR feedstocks across five lifecycle stages reveals the extent to which upstream burdens and allocation choices dictate true removal value (Fig. 4). Among the selected feedstocks, forestry residues consistently yield net-negative outcomes due to low upstream burdens and favorable co-product allocation conditions. Agricultural residues, such as paddy straw, exhibit the greatest potential variability, ranging from marginally net-negative to strongly net-emitting. Purpose-grown feedstocks also achieve net-negativity, regardless of upstream burden assumptions, but their ultimate benefit depends on how land-use change is managed—an issue which remains unaddressed here.[46,74] These results demonstrate that apparent removal can be overstated by an order of magnitude if upstream burdens are ignored. OAB corrects this distortion by carrying forward embedded liabilities to enable assessment of net-zero claims.

This analysis clarifies three scenarios with distinct implications for CDR claims. Forestry residues and purpose-grown biomass consistently yield net-negativity under OAB, supporting their eligibility for use in compensatory CDR markets. In contrast, when biochar is produced from agricultural residues, inclusion of upstream cultivation emissions can render the process net-emitting. In these cases, the benefit lies not in generating offset credits, but in rebalancing upstream liabilities—reducing net emissions in the parent agricultural system and stimulating broader decarbonization. Applying OAB to rice straw shows that BCR can reduce emissions liabilities by up to 60% for the rice straw. Given that rice cultivation contributes nearly half of global agricultural emissions ($\approx$1 GtCO2e/yr)[75,76] and generates roughly 0.24 GtC in residues,[60] this reduction represents a significant mitigation opportunity. However, it should be recognized as emissions reductions within the source system—and not mischaracterized as independent "offset" removal.

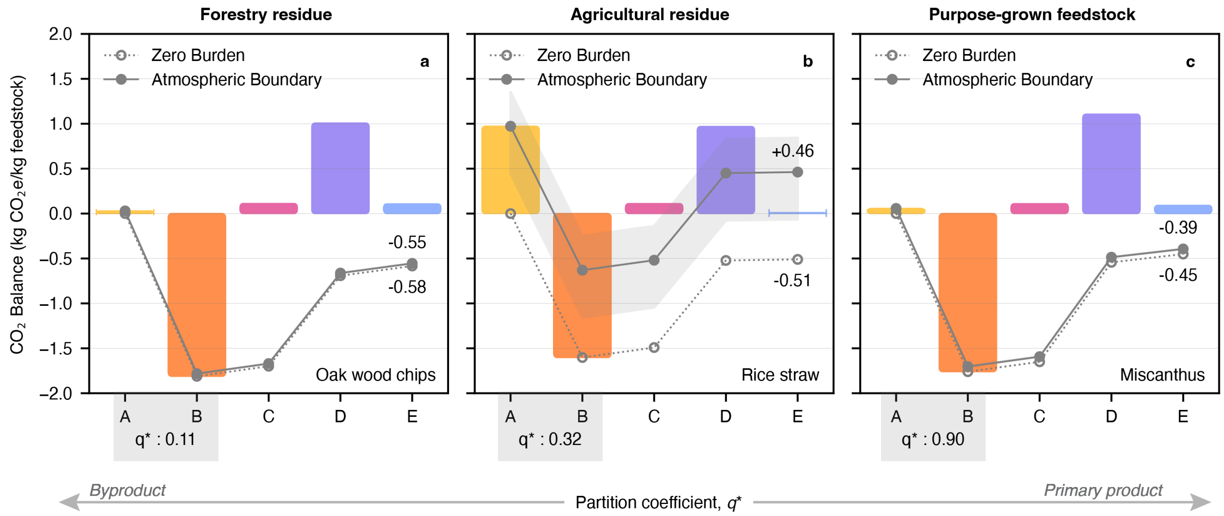


Figure 4: CO_2 balance for biochar production at 500°C from a) wood chips (n = 2), b) paddy straw (n = 4), and c) miscanthus x giganteus (n = 2). Bars represent average emissions (positive) or removals (negative) across five lifecycle stages: A, B, C, D, and E indicate cultivation, biomass capture, biomass processing, pyrolysis loss, and biochar end of life, respectively. Gray scatter plots show cumulative sums with and without cultivation burdens ("atmospheric boundary" (OAB treatment) vs. "zero burden"). Shaded regions reflect the range of cumulative outcomes per feedstock. The partition coefficient q* denotes carbon-based allocation across multifunctional processes. See SI for activity details, product parameters, and q* calculations.

Global implications of the attribution gap in contemporary CDR accounting

Misaligned accounting at the project-level—as demonstrated by BCR—can propagate into a systemic attribution gap when upstream emissions are omitted from crediting boundaries. Unlike over-crediting (unmet performance) or leakage (spatial displacement), the attribution gap arises from a structural misalignment of unfit accounting systems—not a technological failure. High-quality engineered CDR can deliver genuine atmospheric removal—but only if accounting systems consistently true removals from emissions reductions. CDR, in market and policy contexts, is a specific activity that requires a dedicated accounting construction. Each credited removal must be the additive inverse of a quantified emission. Without closure of this balance, credits license continued emissions rather than neutralize them, driving excess atmospheric loading.

Applying OAB to rice straw systems indicates that attribution gaps may generate excess atmospheric loading approaching 0.8GtCO_2e per year[60]—comparable to erasing more than a decade of progress in U.S. power-sector decarbonization[77]—simply by omitting cultivation-phase emissions. By reconciling removal and emissions ledgers OAB prevents this hidden atmospheric debt and directs capital toward verified mitigation outcomes. In this way, carbon accounting functions as core climate infrastructure supporting long-term decarbonization.

Fair and systematic comparison across CDR pathways similarly requires the recognition of embedded burdens under OAB. All pathways require energy and material inputs and should be assessed accordingly to incentivize high-impact project development.[32] . Existing direct air capture (DAC) crediting rules alredy require upstream emissions allocation, incentivizing low-carbon energy sourcing and off-grid configurations.[78] The same discipline is needed for biochar, where net emissions outcomes depend strongly on feedstock origin, baseline disposition, and regional practices.[79] By allocating upstream burdens to proportionally to CDR value, OAB would strengthen the mitigation contribution of biochar while improving agricultural emissions outcomes—rewarding higher-integrity deployment and enabling credible comparison of biochar's removal value relative to other pathways.

These implications extend beyond project integrity to global and intergenerational equity. Without allocation discipline, unmitigated liabilities remain in host countries, obscuring mitigation potential and creating future atmospheric debt (*e.g.* residue-derived biochar can decarbonize rice systems by reducing total emissions by up to 33%). As host countries design decarbonization strategies aligned with future economic growth, retaining domestic mitigation potential may be essential to sovereignty. Transacting removals without OAB risks may exporting benefits while leaving liabilities behind—shifting atmospheric debt to future generations with potentially severe economic and environmental consequences. OAB provides an accurate, interoperable accounting framework to re-balance incentives across crediting and emissions reduction objectives, recognizing the distinct and complementary roles these activities play in achieving long-term net-zero objectives.

Building decision-support infrastructure for markets, policy, and governance

OAB functions as a connective layer linking ground-truth flux data to the normative systems of crediting, inventories, and governance (Fig. 5). It translates measured carbon transfers—the most objective layer of the system—into actionable information by identifying the relevant physical flows and applying explicit attribution functions. By design, OAB avoids subjective constructs such as additionality and baseline setting, preserving both atmospheric integrity and the flexibility needed to scale across jurisdictions.

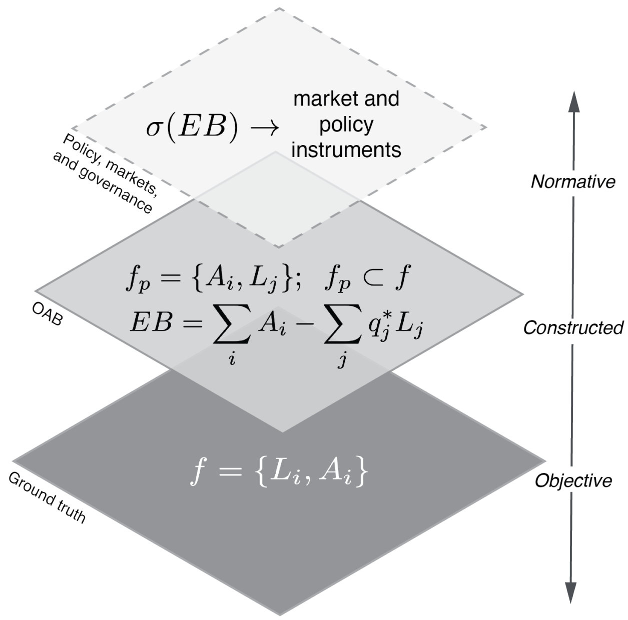


Figure 5: The Objective Atmospheric Basis (OAB) serves as a message-passing layer between physical atmospheric carbon fluxes and the normative systems of policy, crediting, and governance. The bottom layer represents objective asset and liability fluxes of CO_2 to and from the atmosphere, $f = \{A_i, L_i\}$, which exist independent of any accounting system. OAB (middle) selects a project-relevant subset $f_p \subset f$, assigns attribution weights q_i^*, and computes the emissions balance as $EB = \sum_i A_i - \sum_j q_j^* L_j$. Decision makers can consume this with their own activation or interpretation function $\sigma(EB)$ to translate accounting data to markets, inventories, and policy instruments (top). These systems define incentives, eligibility, and credit governance on top of OAB's physically grounded, end-to-end quantification scheme.

By establishing accurate, interoperable accounting foundations and enforcing value chain accountability via environmental ledgers, OAB enables policymakers and market stakeholders to design incentives, allocate capital efficiently, and communicate outcomes transparently. However, the classification of "offset" removals or project-level climate service value remains inherently normative.[21,22,26,27] OAB defines net negativity within explicit system boundaries that may exclude broader agricultural emissions; in multi-output systems, co-products retain liabilities under carbon-based allocation. While alternative allocation strategies are available,[54,80] robust accounting requires transparent, reproducible definitions grounded in causal alignment to atmospheric outcomes. By allocating emissions in proportion to CDR value, OAB provides a reproducible approach while preserving the integrity of atmospheric impact.

Operationalizing OAB will require parallel development across both governance and infrastructure domains: alignment across inventories and registries, robust allocation rules for complex pathways, accessible ledger infrastructure, parallel analysis of indirect effects, and a shift towards ledger-based permanence liability. Detailed implementation priorities are provided in Supplementary Box 1. As Article 6 of the Paris Agreement matures and mechanisms such as the EU's Carbon Removals and Carbon Farming Regulation[81] stimulate demand, ensuring accurate, interoperable, and durable crediting will be essential.

OAB provides a unifying scaffold for this convergence. Grounded in physical flux and compatible with diverse technologies, OAB enables institutions to consistently interpret project-level data while preserving the distinction between emissions reductions and true removals. By closing the attribution gap that arises when accounting systems diverge from the atmospheric carbon balance, OAB strengthens credit integrity, supports efficient capital allocation, and improves comparability across pathways. While it cannot resolve all institutional or technical (e.g., permanence assessment) challenges, OAB reproducibly aligns carbon accounting with the climate system.

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Acknowledgments

The authors gratefully acknowledge support from the Woods Institute for the Environment Environmental Ventures Program and the Stanford Doerr School of Sustainability Accelerator Program.

Author contributions

A.J.R. and K.M. conceptualized the study. A.J.R drafted the initial version and developed the figures and data analysis. K.M. contributed significantly to manuscript drafting, figure development, literature review, and editing. M.N.R. guided accounting formulation. M.N.R., G.M.M., and M.R. contributed to conceptual development, manuscript editing, and final figures. All authors reviewed, edited, and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Supplementary information

Supplementary Information is available for this paper.

Corresponding author

Correspondence and requests for materials should be addressed to Alexandra Ringsby.