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Improved Comparability and System-Wide Verification to Support a Scalable Carbon Credit Market

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Abstract. Achieving net-zero emissions over the coming decades requires unprecedented reductions in anthropogenic emissions of greenhouse gases (GHGs) complemented by a rapid ramp-up in the magnitude of global carbon dioxide removal (CDR). The carbon credit market (CCM) is emerging as a means to finance both emissions reductions and carbon dioxide removal from the atmosphere. To achieve necessary growth on these fronts, the total scope and diversity of projects that are candidates for inclusion in the CCM must expand, necessitating a means of comprehensively assessing the quality of carbon credit projects[1] (CCPs) based on their ability to make quantifiable reductions to GHG concentrations in the atmosphere. Toward a comprehensive quality assessment, we propose a framework to assess and differentiate CCPs based on their estimated impact on atmospheric GHG composition. In parallel, we propose a path towards verification of the aggregated atmospheric impact of CCM actions, since a detectable and attributable signal in atmospheric GHG composition can be viewed as the clearest measure of their climate forcing and, therefore, effectiveness.

[1] A carbon credit project is an activity designed to reduce or avoid greenhouse gas emissions, or remove them from the atmosphere, with each credit frequently defined as representing one metric ton of carbon dioxide equivalent.

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1. Introduction

The urgency for climate action has increased as the impacts of climate change are manifest. These impacts are in part direct consequences of the continued rise in global atmospheric carbon dioxide (CO_2) concentrations (Forster et al., 2025, Friedlingstein et al., 2025). Compounding this rise, the rate of global warming is accelerating due to a continued increase in non-CO_2 greenhouse gases (GHGs) and a recent decline in aerosol-driven cooling (Chen et al., 2024, Yuan et al., 2024, Zhang et al., 2025). As a result, 1.5ºC warming above pre-industrial conditions will be breached within the next decade (Bevacqua et al., 2025, Cannon, 2025, Forster et al., 2025).

Scenarios with a climate outcome below 2°C warming over the 21st century require a rapid large-scale shift away from fossil fuel use towards low-carbon energy sources, reduced energy use, and carbon dioxide removal (IPCC, 2023). Current climate policy efforts remain insufficient as emissions continue to rise globally and the emission gap between current projected trajectories (i.e., accounting for Nationally Determined Contributions, NDCs) and net-zero requirements remains significant (UNEP, 2025). Consequently, there is a strong interest in accelerating emissions reductions while identifying ways to develop and scale up engineered or nature-based carbon dioxide removal (CDR) solutions. Indeed, CDR can play three key roles: 1) complement near-term net emissions reductions, 2) compensate for residual emissions from hard-to-abate sectors when mitigation gets us close to net-zero emissions, or to enable net-negative emissions later in the 21st century and/or 3) bring global temperature back to a desired level after a temporary warming overshoot.

A critical mechanism for CDR, the carbon credit market (CCM), faces systemic challenges (e.g., lack of transparency, inconsistent verification, and the absence of equivalence standards), which hinder its acceptance and scalability (William et al., 2020, Wall Street Journal, 2025, McIntosh et al., 2025). Some reform proposals have emerged and entities such as the Integrity Council for the Voluntary Carbon Market (https://icvcm.org/) are proposing core principles for registries and methodologies. Complementing these efforts, carbon credit issuers are proposing and implementing improved methodologies for advancing Measurement, Reporting, and Verification (MRV). However, assessing and differentiating the overall quality of CCPs remains challenging, especially across diverse project types (Probst et al., 2024).

In this Perspective, we argue that the effectiveness of GHG emissions reduction and removal methods should ultimately be judged by their impact on atmospheric concentrations of CO_2 and/or other GHGs. To that end, we encourage a focus on developing the observational, modeling and operational mechanisms needed for 1) identification and attribution of the aggregated impacts of CCPs on GHG fluxes across a variety of CCP regions (e.g., forest or agricultural eco-regions, cities, industrial basins) that can be aggregated up to larger geo-political domains (such as country-level) and 2) integration of the science efforts (e.g., better quantification, at the relevant scales, of GHG removals and emission reductions and of natural emission uncertainties), into operational CCM considerations. In addition, we propose to develop a quantification framework for comparing CCPs across project types, specifically through the lens of their impact on GHG concentrations in the atmosphere.

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2. State of the Science

We focus this Perspective on assessing the extent to which CCPs can support mitigation actions to reduce the atmospheric concentration of CO_2 and other GHGs, as this is a direct measure of their climate forcing. This is discussed here through two complementary goals: 1) to quantify and attribute the aggregated atmospheric impact of CDR projects or emission changes (including avoided emissions) and 2) to define a framework enabling comparability (also known as fungibility) analysis of CCPs across a broad range of project types (e.g., forest management, waste, industrial or agricultural emission reductions, mangrove restoration, ocean sequestration, biochar). Note that, since this Perspective focuses primarily on the atmospheric composition impact of CCPs, we will not discuss the project-scale verification, as that is already part of the existing evaluation of each CCP during the registration process.

2.1 Atmospheric impact of carbon credit projects

The identification of decreases in atmospheric concentrations of GHGs can be viewed as the ultimate verification that the aggregated impact of carbon removal and emissions reduction projects is effective. Specifically, once carbon removal and/or emissions reduction efforts reach a scale sufficient to be detected at regional to global scales, what will be required to reliably quantify the impact of those efforts on atmospheric GHG concentrations?

The difficulty of global-scale verification can be illustrated by the COVID-related reduction in 2020 CO_2 emissions from decreased transportation, industrial, and economic activities. While this reduction was estimated to be approximately 2.6 $GtCO_2$ (Le Quéré et al., 2021), the observed global mean CO_2 surface concentration did not display a statistically significant response, given the large year-on-year variability of the global CO_2 growth rate (Friedlingstein et al., 2022). The difficulty of identifying a statistically significant response under such a relatively large emission change is a symptom of the large uncertainties in the estimates of the global carbon fluxes, especially with respect to the variability of the natural (land and ocean) components of the carbon cycle (Friedlingstein et al., 2022, 2025, Lovenduski et al. 2021).

Multiple local to regional studies, however, were able to quantify COVID-related emissions reductions. Urban emissions changes were measured using both eddy covariance flux towers (Nicolini et al., 2022, Matthews and Schume, 2022, Vogel et al., 2024) and regional atmospheric inversions (Turner et al., 2020, Yadav et al., 2021, Nalini et al., 2022, Mallia et al., 2023, Roten et al., 2023, Hamilton et al., 2024). More generally, satellite and in situ data can be used to quantify GHG fluxes across urban areas (Lauvaux et al., 2020, Gurney et al., 2021, Ahn et al., 2025), oil and gas basins (Varon et al., 2023, Barkley et al., 2023), agricultural areas (Lauvaux et al., 2020) and large point sources such as power plants (Cusworth et al, 2021, 2023, Nassar et al., 2022, Lin et al., 2023) with overall uncertainties likely small enough to satisfy requirements for monitoring CDR or emissions reduction projects. Quantifying GHG fluxes from representative regions (e.g. major cities / urban corridors, agricultural or forest areas, gas basins) that host CCPs, therefore, could detect a regionally-aggregated atmospheric impact of CCPs more readily than attempting to extract their global signature. This regional work can then be aggregated at the

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scales of nations or continents (Hu et al, 2019, 2025, East et al., 2025) and ultimately merged with the global signature to create a multi-scale system for monitoring the aggregate impacts of CCPs.

Research is however needed to demonstrate the utility of these approaches with current CCPs. Indeed, the most recent global estimate of annual retired[2] carbon credits (Haya et al., 2025) amounts to approximately 220 Mt CO_2 (millions of tons of CO_2) per year. Since this is an order of magnitude smaller than the estimated COVID signal, their combined impact is currently not detectable at a global scale with our existing network of observations. At the project scale, the largest CCP (the Mai Ndombe Project, Haya et al., 2025) retired approximately 9 $MtCO_2$ in 2024, similar in magnitude to the annual CO_2 emissions of a medium-sized (1000 MW) coal power plant, albeit with a much more spatially diffuse footprint. It is not clear when regional emissions measurement capabilities will be able to quantify the impacts of regionally aggregated CCP efforts.

These various discussion points indicate the need for a next-generation carbon credit verification system, targeting the atmospheric impact of CCPs and mitigation as soon as they can be quantified regionally and then verified globally by the time their combined global scale reaches 1 $GtCO_2$ per year or more, possibly within the next 10 years through a combination of nature-based and engineered solutions (Nemet et al., 2024). The verification system should be based on a network of measurements (ground based, airborne, satellites, Carroll et al., 2025) and modeling tools (inverse, process-based, bookkeeping and global Earth-system modeling). It will also need to include as much relevant proxy data (e.g., activity data, biomass estimates) as possible to maximize our ability to constrain top-down or bottom-up emission estimates. At the same time, it will be critical to continue to improve our understanding of CO_2 and methane natural sources and sinks variability, since that will have a direct impact on the ability to attribute reductions and removals to CCPs.

2.2 The Atmospheric Impact Framework (AIF)

The current distribution of retired carbon credits (in terms of $MtCO_2$ equivalent) is primarily driven by forestry and land use and renewable energy projects (Forest Trends, 2024). Within forestry and land use, most of the projects consist of REDD+ (Reducing Emissions from Deforestation and forest Degradation in developing countries, 75-80%), followed by afforestation, reforestation, and revegetation (10-15%), followed by improved forest management (1-5%) and blue carbon (1-5%) (Forest Trends, 2024). In all cases, the impact of CCPs is expressed in units of tons of carbon dioxide equivalent (1 credit is, by definition, equal to 1 ton of CO_2eq). This implies that any credits are expected to have the same impact on atmospheric composition and therefore climate. Conceptually, this would seem unlikely since some credits are issued based on permanent removal of CO_2 from the air (direct air capture), while others are issued based on storage of carbon in ecosystems (REDD+) or emissions that might

[2] A "retired carbon credit" is a carbon credit that is permanently removed from the market, ensuring it cannot be resold, traded, or double-claimed, and allowing the owner to claim the environmental benefit for their sustainability goals. This retirement is recorded in a registry, effectively "consuming" the credit so its emissions reduction is used only once.

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otherwise have occurred (avoided emissions, including methane). This equivalency issue is widely recognized (Probst et al., 2024), yet there is still no consensus on how to best solve it.

Meanwhile, emerging technologies are further broadening the range of project types, and the ability to assess their respective performance is becoming increasingly challenging. For example, in an ocean alkalinity enhancement experiment, the process of CO_2 exchange with the atmosphere, and hence measurable atmospheric impact, could be delayed and occur at very different locations than the ocean alkalinity addition due to oceanic circulation (Zhou et al., 2025). Conversely, the CO_2 removed from the atmosphere through a direct air capture plant is an instantaneous and local process. Consequently, in addition to parameters such as additionality and permanence that are currently identified in registries and used by rating agencies for evaluating the quality of carbon credits, we need to define a common yardstick for impact on atmospheric GHG concentrations that incorporates aspects of verifiability and uncertainty in the estimated reduction (or confidence in the quantification).

We propose to build the Atmospheric Impact Framework (AIF) to enable comparability of CCPs using a consistent system. Under this framework, in addition to considering frequently assessed quantities such as permanence, leakage and additionality, we aim to identify the relevance of each CCP to near-term or long-term horizons. This will be performed by estimating the risk that the reported amount of carbon credits will not be delivered as promised, owing either to errors in the initial quantification or in estimates of permanence. In particular, this risk analysis will consider the realism of each CCP baseline (i.e., the counterfactual to the conditions associated with the project) over its duration. It can be expected that, in many cases, the uncertainty on the CCP baseline grows over time, similar to the growth in scenario uncertainty with time in climate projections (Hawkins and Sutton, 2009). In the case of a forestry-based CCP, for example, it is reasonable to assume that counterfactual forest outcomes are more predictable in the near term than in the distant future.

The outcome of this analysis is an adjustment factor to be applied to a CCP's issued tons as reported by its respective registry, to reflect our overall understanding of the ability and effectiveness of a project to deliver a climate impact. This adjustment factor can be expressed conceptually as:

$$\mathrm{AF}(t_0, H) = \int_{t_0}^{t_0+H} I(t)\, D(t)\, dt \,/ \int_{t_0}^{t_0+H} I_R(t)\, dt \qquad \text{(Eq. 1)}$$

In this equation, $\mathrm{AF}(t_0, H)$ is the adjustment factor to be applied to the CCP's estimated credits multiplicatively. This adjustment factor is calculated over a time horizon H, with t_0 as the reference year. *I(t)* is the time-dependent atmospheric impact of a single credit from the specific CCP. This time-dependent impact can be measured in terms of a CCP-induced change to atmospheric GHG concentration, radiative forcing, or global temperature. *D(t)* is a time-dependent discount measuring the risk of a CCP not delivering its estimated credits, e.g., from baseline uncertainty or reversibility risk. By definition, a no-risk project has a discount factor of 1. $I_R(t)$ is the equivalent of *I(t)* but for a reference ton[3]. Under the normalization in Eq. (1), a no-risk project that behaves like the reference ton

[3] In the context of carbon credits, a reference ton (commonly referred to as a metric ton of carbon dioxide equivalent or tCO2e) is the standardized unit of measurement used to quantify greenhouse gas emission reductions or removals.

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has a score of 1 for each horizon H. The goal of the AIF is to define the variables in Eq. (1) for each CCP, based on our best understanding, to compute AF.

Because it is expected that our scientific understanding and our ability to verify (as discussed in section 2.1) will evolve over time, we anticipate that the AIF analysis will require periodic re-evaluation, possibly on an annual basis. This iterative process will allow for updates to the evaluation of the CCPs, especially as they become considerably larger and new approaches become available.

3. Next Steps

The proposed initiative in this commentary aims to help the CCM reach a sufficient scale to significantly impact climate. For this, we propose to:

- Create a framework that leads to a complete, transparent, and traceable assessment of CCPs, with a specific lens on their impact on atmospheric CO_2 and/or other GHGs
- Reduce the uncertainty associated with naturally-occurring sinks in the terrestrial biosphere and the ocean
- Inform policy and investment decisions through CCP equivalence metrics
- Align new scientific insights and availability of atmospheric verification with CCM mechanisms through regular updates

To achieve those goals, we propose the following next steps:

- Pilot the Atmospheric Impact Framework (AIF): Launch pilot assessments with the AIF of specific projects across various types of mitigation and CDR approaches, including an analysis of associated economic aspects outside the scope of the project itself, such as market leakage and financial additionality. Define reference criteria and an associated set of equivalence parameters, potentially leading to guidance for registries and other CCM actors to provide the information relevant to AIF estimations. Update annually through an expert panel review to reflect evolving scientific understanding.

- Expand Regional Carbon Budget Analyses: Prioritize regions with high relevance for nature-based and engineered carbon projects. Build on approaches like RECCAP3 (Canadell et al., 2025) to establish new regional and national (and possibly subnational where applicable) baselines and understanding of changes in anthropogenic and natural carbon fluxes and stocks, including horizontal fluxes (e.g., from trade) at the macroscopic level.

- Enhance Annual Global Carbon Budget (GCB) Updates: Continue to refine the GCB with improved data integration, enhanced uncertainty quantification, and incorporation of emerging data sources (e.g., data assimilation, satellite platforms, high-resolution proxy data to constrain inventories of anthropogenic and natural emissions).

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- Integrate existing and emerging CDR Pathways into Earth System Models (ESMs): Coordinate Earth system modeling efforts to incorporate the necessary processes to reflect the diversity of CDR technologies and strategies and their impact on the climate system. Establish model experiment design protocols to evaluate long-term impacts of CDR deployment, to understand the magnitude and uncertainty of Earth system couplings and feedback effects under multiple pathways.

In parallel, we need to develop a comprehensive strategy to enable the verification of the atmospheric impact of CCPs, through a multi-scale approach that will:

- Strengthen Observational Networks and Platforms: Design and potentially deploy satellite missions, airborne campaigns, and in situ monitoring networks to target key regions. Define a multi-scale (local, regional and global) approach that utilizes current and next-generation CO_2 and methane (and ultimately other GHGs) sensors, in combination with data assimilation and inversion systems incorporating all relevant activity data, to better define emissions and sinks and enable attribution of changes at a scale relevant for CCM verification.

- Perform a knowledge gap analysis at multiple scales: CCPs are included in national inventories, which can then be aggregated into regional and global assessments (such as RECCAP and GCB mentioned above), with the regional and global feedbacks captured by the ESMs. The analysis of potential mismatches between observations and bottom-up assessments can help identify the gaps in our understanding at those various scales.

We believe that these steps, and their continual updates, will ultimately build a comprehensive and verifiable analysis that allows for the scaling of CCPs to become a significant and trusted tool for climate change mitigation.

Author contributions

JFL, PF, BO and SS designed the workshop from which this paper originates. JFL and PF designed the original draft of the paper. JFL prepared the manuscript with contributions from all co-authors.

Competing interests

None of the co-authors have potential conflicts of interests.

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