COMMENTARY

Achieving accurate regional carbon-sink accounting and its significance for “missing” carbon sinks

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In the 2019 revision of the IPCC’s 2006 national inventory guidelines, the atmospheric inversion of greenhouse gas (GHG) emissions based on atmospheric concentrations was proposed for the first time to better support inventory verification initiatives. Thus, a globally unified verification reference standard was formulated, commonly known as the “top-down inversion” method.[1] The characteristics of this method are its thorough coverage, strong timeliness, and low bias. The 2019 IPCC guideline’s “refinement” can effectively improve the accuracy and credibility of the bottom-up method that is currently being used to account for the carbon (C) source/sink status of various ecosystem types. It will be necessary to couple and synchronize atmospheric and ecological C processes to accurately calculate the status of ecosystem C sinks while also reducing errors introduced by anthropogenic-based emission uncertainties. Therefore, to maintain terrestrial-atmospheric C exchange monitor consistency while truly achieving accurate ecosystem C sink accounting, these methods from independent evaluating results require unification.

The “zero C sink” equilibrium state of mature ecosystems exists on both global and regional scales (i.e., tropical, temperate, and cold regional scales). Therefore, when C cycling models are used to calculate ecosystem C budgets, the average state within a specific period is typically reflected. However, on an interannual scale, the C-sink capacity will never truly be zero; rather, it will fluctuate around its equilibrium state. This fluctuation is closely related to changes in environmental conditions (i.e., climate), which are difficult to reveal and calculate in practice. However, due to a lack of consensus on the key C sequestration processes and driving mechanisms within the three main natural ecosystem C-sink types (i.e., soil, vegetation, and inland waterbodies), the current accounting methods and standards used to accurately estimate the capacity of ecosystem C sinks lack uniformity.

CARBON-SINK ACCOUNTING OF SOIL, VEGETATION, AND INLAND WATERBODIES

Enhancing the soil C sequestration capacity is an important measure to slow increases in atmospheric carbon dioxide (CO_2) concentrations while being a critical means by which to achieve indirect C emission reductions. Comparatively, vegetation-based C pools are more efficient than soil-based C pools, and this is particularly true for aboveground vegetation components. At present, many studies have combined vegetation C pools with remote sensing observations to explore vegetation C-sink changes at different spatial and temporal scales. For soil C pools, early studies primarily focused on soil organic C pools and key associative chemical components. Little attention has yet been paid to dynamic changes in soil inorganic C pools in the form of carbonate and particulate organic C and mineral-bound organic C components, whose stability differs. Moreover, our understanding of the accumulation and decomposition rates associated with these key soil C pool components and their response to a warming climate is largely inadequate (Figure 1).

Known soil organic C pool characteristics are their extensive background value, their high spatial heterogeneity, and their complex composition. Fractional differences in soil organic C components also differ significantly in source, formation mechanism, and response to global climate change. It is therefore difficult to determine the extent of short-term soil C pool change. It is equally difficult to reveal componential soil C changes that arise from different C sources and are subject to different stability levels, limiting our understanding of the soil C-sink effect. Previous studies have focused on the chemical structure of soil C and the protective effect of secondary minerals on organic C regarding soil C formation, transformation, and stabilization mechanisms. Moreover, we still do not fully understand how biological factors affect the formation, transformation, and stability of soil organic C. However, we do know that plant residue is the most important soil organic C source, while microorganisms are the core drivers of soil organic C formation and transformation processes. Plant residue, microorganisms, and their combined interactions are bound to drive dynamic changes in organic soil C. Therefore, revealing the key roles that biotic and abiotic factors play in the formation, transformation, and stability of soil organic C processes is the basis for accurate soil C sink accounting and the foundation for developing soil C-sink enhancement technology.

Current observational data on belowground vegetation C pools remain relatively limited. Combined with observed surface data, aboveground C-sink dynamics can be successfully inverted; however, using remote sensing data to simulate belowground C pool processes and associated dynamic changes is not ideal. At the same time, scale asynchrony among observational data also increases vegetation C-sink accounting uncertainty. Additionally, existing vegetation C pool monitoring data do not include information on the horizontal transfer of vegetation C, which to some extent increases C-sink accounting uncertainty.

Many factors affect the size, dynamic, and spatial distributions of vegetation C sinks (i.e., climate change, atmospheric chemical composition, and natural and anthropogenic disturbances). However, our understanding of the vegetation C-sink mechanisms driven by different biotic and abiotic factors remain limited, as well as the way ecological engineering and ecosystem management practices effect vegetation C sinks. Therefore, it is necessary to strengthen our observational capacity of different vegetation components while integrating multisource data. This will help better reveal the influencing mechanisms of bio-abiotic factors and ecosystem management measures during vegetation C-sink formation processes to facilitate the assessment method and improve the estimation accuracy of vegetation C sinks. Additionally, revealing the mechanisms that underly plant growth, soil microbial activities, and plant-soil interactions is necessary for both plant and soil C-sink accounting.[2]

In addition to soil and vegetation C sinks, inland water is both an important C reservoir and a C-absorbing engine under high C turnover rates. The vertical C exchange is the primary C sequestration function of inland water that occurs in conjunction with atmosphere and sediment burial processes. Moreover, C exchange processes that include surrounding waterbodies occur through horizontal water flow (Figure 1). There is a lack of systematic analysis on the functional characteristics associated with spatial and temporal inland water C-sink dynamics. Additionally, a wetland ecosystem river-lake-offshore database has been generated to provide a list of associated C-sink function and uncertainty estimates at a regional scale. This will provide a more accurate C-sink accounting system. Compared with terrestrial ecosystems, the advantages of coastal “blue C” zones are their high C burial rate and long-term continuous C sequestration capacity.[3] At present, it is imperative that we integrate fixed-point control experiments, network observations, and model simulation research methods to conduct systematic point-to-surface studies at both micro- and macroscales. We must also understand coastal blue C wetland ecosystem patterns to better clarify associative responses and adaptation mechanisms under prospective environmental change, to improve our scientifically based understanding of coastal blue C wetland sink mechanisms while protecting future C-sink intensity.

Atmospheric inversion is an effective method to quantify global and regional surface C flux through atmospheric transport models and data assimilation methods, using quantitative monitoring practices associated with changes in atmospheric CO_2 concentrations. Long-term international research has been

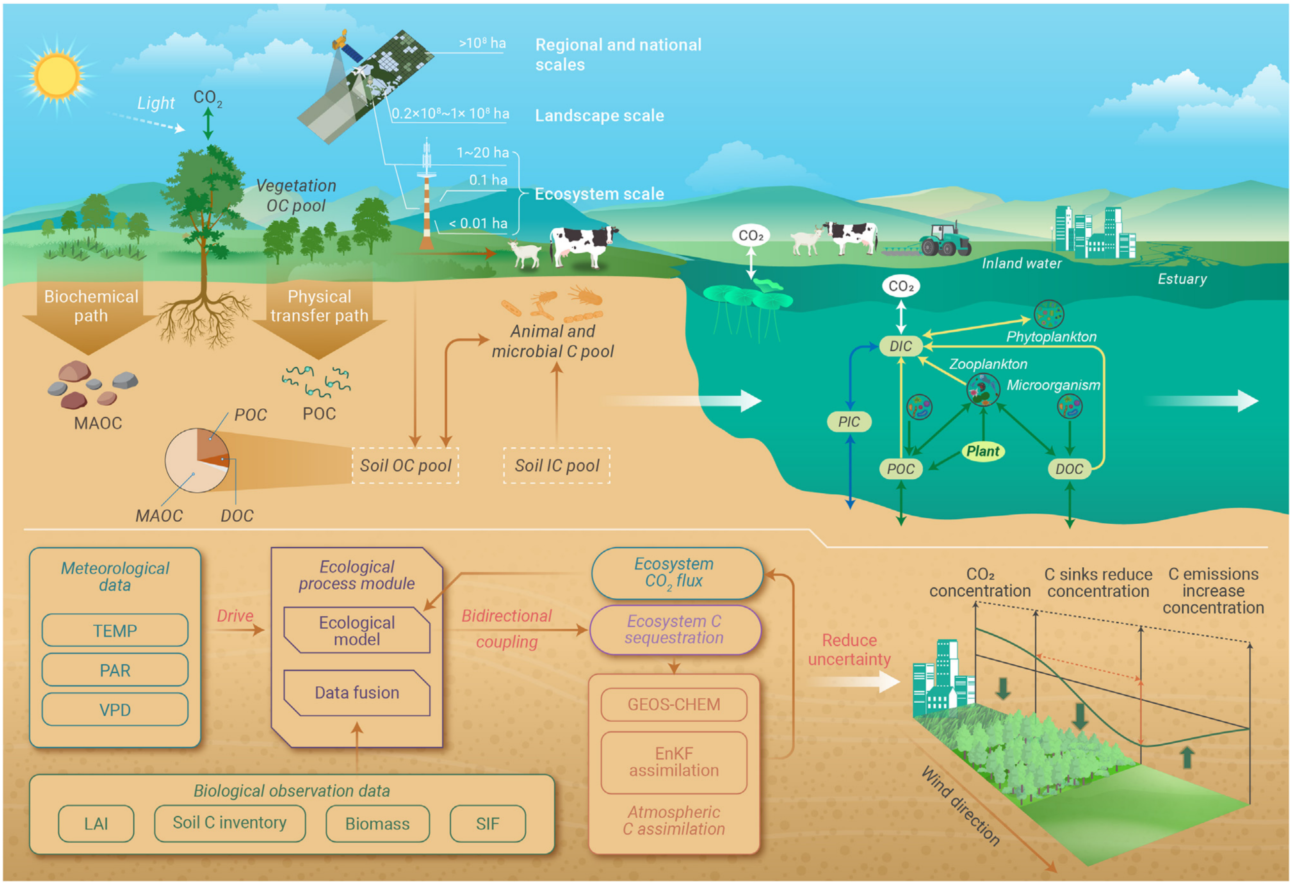

Figure 1. Soil, vegetation, and inland water carbon pool, as well as uncertainty reductions in terrestrial ecosystem carbon-sink accounting through the coupling of multisource data MAOC, mineral-associated organic carbon; NPP, net primary productivity; OC, organic carbon; IC, inorganic carbon; SOC, soil organic carbon; CO_2, carbon dioxide; PIC, particulate inorganic carbon; POC, particulate inorganic carbon; DIC, dissolved inorganic carbon; DOC, dissolved organic carbon; TEMP, temperature; PAR, photosynthetically active radiation; VPD, vapor pressure difference; LAI, leaf area index; SIF, solar-induced fluorescence; GEOS-CHEM, Goddard Earth Observing System Chemistry-Climate Model; EnKF, ensemble Kalman filter.

conducted using top-down atmospheric inversion methods; however, it is presently in its preliminary stage with regard to accurate C-sink accounting and target applications for the global inventory. Although the atmospheric inversion method has advantages in large-scale and high-frequency C source and sink calculations, there remain considerable uncertainties with regard to the accurate calculation of C budgets within various ecosystems.[4] The main reason for this uncertainty is that the current method cannot effectively subdivide nor quantitatively distinguish the atmospheric CO_2 change contribution from that of other processes, while the usage of multisource observational data is currently insufficient. Existing studies have assumed that anthropogenic emission data are accurate and that only ecosystem C flux processes are optimized through observations. Research results based on this assumption show that top-down inversion method calculation results differ from those of the bottom-up method, and the source of these differences cannot separately be determined, which restricts accurate C-sink accounting. Therefore, for its future development, there should be a greater quantitative emphasis on distinguishing and calculating various C emissions and sinks. By coupling ecosystem and anthropogenic activity process models, the collective constraints and the multiobjective collaborative optimization of multisource observational data can be realized (Figure 1). The top-down and bottom-up methods can be combined into a unified calibration system, which can effectively be used to detect existing problems specific to these two independent methods. Through improvements to mechanisms, algorithms, observations, and models, we can achieve more accurate C-sink accounting.

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DECLARATION OF INTERESTS

The authors declare no competing interests.