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Preface: The role of remote sensing to improve modeling of carbon quantities and quality of carbon credits☆

Climate change represents one of the most profound and urgent challenges facing humanity. Anthropogenic greenhouse gas emissions, particularly carbon dioxide, continue to rise, intensifying global warming and threatening the stability of ecosystems, economies, and societies worldwide (IPCC, 2023). Addressing this challenge requires not only rapid reductions in fossil fuel emissions but also the development and deployment of strategies that can remove carbon from the atmosphere and store it securely in terrestrial and oceanic systems (Smith et al., 2016).

Among these strategies, nature-based solutions (NbS, Griscom et al., 2017) have gained increasing prominence. Through the conservation, restoration, and improved management of agriculture, forestry, and other land uses, NbS can provide measurable reductions and removals of carbon while simultaneously supporting biodiversity, enhancing resilience, and generating co-benefits for communities. The credibility and scalability of NbS, however, depend critically on robust measurement, reporting, and verification (MRV) frameworks (Balmford et al., 2023). In this regard, incentive mechanisms such as carbon credit programs are playing an expanding role in financing NbS. Yet the integrity of such programs hinges on the accuracy, transparency, and reproducibility of the methods used to estimate carbon emission, fluxes, and stocks, as well as their associated uncertainties.

Remote sensing offers a uniquely powerful set of tools to address these requirements. Advances in satellite, airborne, and proximal sensing platforms, together with the proliferation of eddy covariance networks, large-scale ecological datasets, and rapid developments in machine learning and data assimilation, are transforming our capacity to observe, quantify, and model carbon dynamics across spatial and temporal scales. From fine-scale monitoring of parcels and ownership units to national and global inventories, remote sensing enables the consistent and independent assessment of biomass, productivity, and greenhouse gas fluxes that is essential for both science and policy.

This special issue of Remote Sensing of Environment brings together 13 contributions that collectively advance the science and practice of carbon monitoring. These studies present methodological innovations, novel datasets, and rigorous evaluations that respond directly to the demands of carbon accounting in a changing climate. They address the full spectrum of the carbon cycle, ranging from biomass and carbon stock estimation to ecosystem productivity modeling and the direct atmospheric detection of greenhouse gas emissions. Together, they demonstrate how remote sensing can underpin credible MRV systems, thereby strengthening the scientific foundations of NbS and enhancing the effectiveness of existing and emerging carbon credit mechanisms.

In the sections that follow, we synthesize these contributions into three thematic categories: (1) Biomass and Carbon Stock Estimation, (2) Productivity Modeling and Process Understanding, and (3) Greenhouse Gas Emissions and Atmospheric Monitoring. Within each theme, the papers highlight both the state of the art and the remaining challenges, charting pathways for future research that will further align carbon science with the needs of climate mitigation and sustainable development.

1. Biomass and carbon stock estimation

The accurate quantification of aboveground biomass and carbon stock remains a cornerstone of carbon accounting and is fundamental to evaluating the effectiveness of NbS. Despite decades of progress, considerable challenges persist in developing biomass datasets that are both spatially explicit and temporally dynamic, while maintaining high accuracy and robust uncertainty characterization. Several contributions in this special issue address these challenges through both conceptual reviews and empirical advances, spanning from project-level monitoring to national-scale inventories.

Wheeler et al. (2026) critically evaluates the role of Forest-focused Natural Climate Solutions (F-NCS) in the voluntary carbon market (VCM). Although F-NCS activities, such as forest protection and restoration, are central to climate mitigation, the study highlights integrity concerns arising from inconsistent implementation and vague accounting rules, which have contributed to over-crediting and eroded market confidence. To strengthen credibility, the review synthesizes emerging approaches for monitoring carbon stock change, additionality, leakage, and non-durability, emphasizing the integration of remote sensing, federated forest plot databases, causal inference methods, and machine learning. The authors recommend that carbon standards evolve alongside scientific advances, including the incorporation of high-resolution carbon maps and the explicit quantification of leakage and non-durability. These insights point a potential pathway toward more accurate and transparent carbon accounting within voluntary markets. Atzberger et al. (2025) introduces a scalable, annual aboveground biomass product designed to support the monitoring, reporting, and verification of ecosystem restoration projects in Brazil. This study employs self-supervised learning on multispectral time series from Landsat

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and Sentinel-2, combined with Global Ecosystem Dynamics Investigation (GEDI) data, to generate biomass maps at 10–30 m resolution spanning more than a decade. The resulting product demonstrates superior accuracy compared with existing global biomass datasets and is particularly valuable for restoration contexts dominated by smallholder farms, where transparent and repeatable monitoring is essential for participation in carbon markets. Complementing this large-scale approach, Hong et al. (2025) explores the integration of laboratory soil spectral libraries with satellite observations to improve estimates of soil organic carbon (SOC). Through the use of simulated hyperspectral data and advanced machine learning models, the study demonstrates that legacy soil spectral libraries can be harnessed to enable satellite-driven SOC mapping. This work highlights an important pathway to extend fine-scale laboratory knowledge into operational, landscape-scale carbon monitoring. At management scales, the issue of uncertainty quantification becomes particularly pressing. Johnson et al. (2025) addresses this by developing a framework for parcel-level uncertainty estimation in aboveground biomass maps. By combining multiple sources of error, including reference data, sampling variability, spatial autocorrelation, and auxiliary data, the study quantifies uncertainty estimates for each of over 2000 ownership parcels. The study reveals that residual variance, particularly from spatial autocorrelation, is the dominant source of uncertainty at small area scales, and proposes a parsimonious regression model linking parcel characteristics to standard error. This provides landowners and policymakers with a practical tool for reporting biomass uncertainty in ways that are compatible with IPCC guidelines and carbon credit requirements. The importance of national-scale, high-resolution mapping is exemplified by the first 10 m resolution forest structure and carbon stock maps developed for Japan (Li et al., 2024b). By integrating Sentinel-2 time series, ALOS PALSAR-2 SAR, topographic data, and extensive airborne LiDAR data, the study estimates Japan's total aboveground carbon stock at approximately 1440.26 ± 564.58 Tg. The maps reveal strong regional contrasts in carbon density, with higher values in the south and lower stocks in northern regions, and they outperform existing international products such as ESA CCI and GEDI L4B. Beyond advancing scientific understanding of forest structure, these products provide decision-makers in Japan with actionable information to support both domestic carbon inventories and international reporting obligations.

2. Productivity modeling and process understanding

Although biomass and carbon stock mapping provide essential snapshots of carbon pools, the accurate quantification of ecosystem productivity and carbon fluxes is equally critical for understanding carbon dynamics over time. Gross primary production (GPP), net primary production (NPP), and related water-carbon interactions govern the capacity of ecosystems to sequester carbon and respond to climate variability. Yet, representing these processes consistently across scales remains a formidable challenge. The contributions in this special issue advance productivity modeling by introducing novel conceptual frameworks, refining light-use efficiency (LUE) models, and integrating flux tower observations with remote sensing and machine learning. Collectively, these studies deepen process understanding while enhancing the operational relevance of productivity estimates.

Using causal inference methods, Dang et al. (2024) demonstrates that interannual variability of net ecosystem production (NEP) is predominantly regulated by water availability and temperature, with vapor pressure deficit playing a secondary role. By applying convergent cross-mapping to FLUXNET tower observations, TRENDY process-based models, and FLUXCOM machine learning products, their study uncovers clear spatial patterns: energy limitation controls fluxes in higher latitudes, whereas water limitation dominates in arid and semi-arid regions. Importantly, the causal influence of climate drivers on NEP appears to be weakening in the temporal domain, suggesting that land-atmosphere interactions are being altered under climate change. At the tower-to-regional scale, the treatment of vegetation heterogeneity within flux footprints emerges as another key issue. Zou et al. (2025) shows that neglecting sub-grid variability in vegetation composition leads to systematic biases when upscaling evapotranspiration and GPP from eddy covariance sites. By training a deep graph convolutional network with inputs of vegetation indices and other variables for residual correction, their study greatly improved prediction accuracy, for example, with the R^2 value increasing from 0.9098 to 0.9479. This work underscores that flux tower measurements cannot be simply assumed to represent homogeneous footprints and that accounting for heterogeneity is essential for robust upscaling.

Advances in modeling frameworks are represented by the EXP-CASA model, a reformulated light-use efficiency approach (Chen et al., 2025). By expressing the fraction of photosynthetically active radiation (FPAR) as a power function of vegetation indices and modeling environmental stress through a compact exponential-power function, EXP-CASA allows parameters to be estimated and tested directly using FLUXNET observations. Validated across 121 sites representing eight International Geosphere–Biosphere Programme (IGBP) land cover classes, the model achieves superior accuracy compared to standard CASA and GLASS-NPP products. Notably, the approach explicitly addresses the issue of vegetation index saturation, offering greater stability and sensitivity in capturing site-level variability and anomalies. Long-term site-level analyses provide further insights into ecosystem functioning. Pan et al. (2024) examines two decades of carbon and water fluxes across four mature deciduous broadleaf forests in North America. Their study demonstrates that while warmer winters and earlier springs lengthen the growing season, these shifts do not necessarily result in higher annual productivity. Summer stress often counterbalances spring gains, limiting net increases in GPP. Other contributions focus on the refinement of satellite-derived productivity products for specific biomes. For Mediterranean Aleppo pine forests, the Copernicus GDMP product was found to underestimate GPP during cold periods and fail to adequately represent water stress (Chebbi et al., 2025). By removing the temperature scalar and incorporating soil moisture constraints, a refined product achieved much closer alignment with eddy covariance data, effectively doubling the proportion of estimates meeting optimal accuracy requirements. In grassland ecosystems, validation of the CASA model with field observations across multiple perennial grass species demonstrated that incorporating environmental stress scalars significantly improved accuracy at both daily and seasonal scales (Zhang et al., 2025). These results emphasize the practical value of an improved CASA framework for real-time, remote sensing-based assessments of grassland productivity.

3. Greenhouse gas emissions and atmospheric monitoring

Beyond biomass and productivity, direct observation and attribution of greenhouse gas emissions represent a critical frontier for carbon monitoring. Remote sensing of atmospheric constituents offers the opportunity to constrain emission inventories, identify hotspots, and refine models that inform both science and policy. Two papers in this special issue advance the ability to detect, quantify, and correct greenhouse gas fluxes from space.

Li et al. (2024a) addresses the persistent problem of biases in satellite methane retrievals by developing random forest prediction models trained on GOSAT XCH_4 retrievals with TROPOMI band ratios used as key proxy variables. The approach enabled the generation of daily global XCH_4 maps for 2021 at a 0.05° grid resolution. Validation against TCCON ground-based observations showed markedly improved performance compared to the operational TROPOMI product, with a correlation coefficient of 0.91 and an RMSE of 17.16 ppb. This framework offers a computationally efficient means to produce global methane maps that surpass traditional full-physics algorithms, thereby improving the capacity to monitor methane emissions from diverse sectors in support of carbon accounting and sustainable development. Another contribution focuses on urban CO_2 emissions in China's Yangtze River Delta, combining OCO-2 satellite retrievals with Weather Research and Forecasting (WRF)-Chem simulations (Sheng et al., 2025). The study demonstrates the effectiveness of local Moran's *I* statistics to detect localized anthropogenic XCO_2 enhancements. Average increases of 1.36–4.41 ppm were observed near major cities and industrial centers, with a focused case study over Nanjing revealing peaks of 2.26–4.72 ppm. Further WRF-Chem simulations estimate Nanjing's daily CO_2 emissions at 0.65 ± 0.15 $MtCO_2$/day, a value differing from EDGAR inventories by -10.5 % to $+77.3$ %. Such differences were attributed to transport dynamics, background definition, and prior emissions. This work illustrates a robust, observation-based approach to constrain urban CO_2 emissions, providing independent checks on bottom-up inventories and advancing methods for urban carbon monitoring.

This special issue offers an important step forward in the application of remote sensing to carbon monitoring, bringing fresh insights into biomass mapping, productivity modeling, and greenhouse gas monitoring. Together, the studies presented here extend the scope of earlier work in *Remote Sensing of Environment* and introduce new directions that can inform both scientific scholarship and practical implementation. We anticipate that this collection will serve as a basis for continued innovation and collaboration, advancing the role of remote sensing in supporting carbon credit mechanisms, NbS, and broader climate change mitigation efforts.

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