

The Supporting Role and Challenges of Remote Sensing Technology in Whole-Process Carbon Emission Accounting

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Abstract

Traditional carbon emission accounting has long been constrained by insufficient spatiotemporal resolution, limited coverage, and inadequate dynamic monitoring capabilities. Remote sensing technology, leveraging its inherent advantages of non-contact observation, synchronous wide-area sensing, and multi-scale dynamic tracking, has been deeply integrated into the entire process of carbon emission accounting, emerging as a pivotal force for addressing these challenges. Combined with practical application examples of technologies such as night light remote sensing and LiDAR, it deeply analyzes the core technical challenges in accounting accuracy control, multi-source heterogeneous data fusion, and industry-specific accounting method adaptation. Research has shown that remote sensing technology can construct a 1km-scale high-resolution carbon emission spatial grid. The correlation coefficient between the vegetation net primary productivity inverted by the CASA model and the ground measured values ranges from 0.6–0.9. However, factors including observation environmental interferences, inversion algorithm limitations, and industrial emission heterogeneity render the issue of data uncertainty highly pronounced. This article proposes a targeted technological optimization path to enhance the scientific and accurate accounting of carbon emissions throughout the entire process, and provide practical reference for the implementation of the "dual carbon" strategic goals.

Keywords

Remote Sensing Technology; Carbon Emission Accounting; Carbon Sources and Sinks; Whole-Process Support; Accounting Accuracy.

1. Introduction

Realizing "carbon peak and carbon neutrality" is a major strategic decision made by China based on the overall construction of ecological civilization and in response to the trend of global climate governance. Accurate and efficient carbon emission accounting is the core fundamental guarantee for building a solid foundation for climate action implementation and ensuring the effectiveness of emission reduction targets. In the current total anthropogenic carbon emissions in China, cities, as the core of population and industrial agglomeration, contribute more than 80%, and their refined emission reduction management has become a key lever for the "dual carbon" work. However, traditional carbon emission accounting relies heavily on the inventory method as the core technical means and relies heavily on statistical report data from various departments. This not only leads to data fragmentation and inconsistent accounting standards across regions and industries, but also has significant data lag due to statistical cycle limitations. It mostly focuses on macro scales at the provincial level and above, with generally low spatial resolution and insufficient update frequency, making it difficult to adapt to the refined scale of carbon emission monitoring, quota allocation, and regulatory verification needs of urban functional zones, industrial parks, and key enterprises. The updated IPCC Guidelines for National Greenhouse Gas Inventories in 2019 have officially incorporated remote sensing inversion methods into the global carbon balance accounting technology framework, providing

important technical support for breaking through traditional accounting bottlenecks and building a dynamic accounting system throughout the entire process. Remote sensing technology relies on the efficient capture capability of multi-band sensors for carbon cycle-related surface parameters, which can quickly obtain spatiotemporal dynamic change data of carbon sources and sinks [1], effectively filling the gaps in coverage, timeliness, and spatial accuracy of traditional accounting methods. Based on this, this article focuses on the entire process of carbon emission accounting, systematically analyzes the support mechanism and practical application bottlenecks of remote sensing technology, and verifies the adaptation scenarios and application efficiency of different remote sensing technologies with measured data. It provides theoretical reference and practical support for optimizing the carbon emission accounting technology system, improving the credibility and applicability of accounting results, and helping carbon management work upgrade from macro control to refinement and precision.

2. The Fundamental Support of Remote Sensing Technology in Carbon Emission Accounting

Remote sensing technology, centered on satellites and drones, forges a multidimensional collaborative observation matrix, integrating optical, thermal infrared, and synthetic aperture radar (SAR) sensors—each fulfilling its unique role. Boasting core advantages of wide macro coverage, high-precision multispectral analysis, and sensitive temporal dynamic tracking, it lays a solid standardized underlying data foundation for the entire process of carbon emission accounting. This technological approach not only effectively supports data supply for each link of the accounting process, but also fundamentally breaks the inherent constraints of the traditional accounting model that prioritizes single-point monitoring over overall coverage, effectively addressing the shortcomings of fragmented monitoring scope and inadequate spatial representativeness in the past [2]. Among them, the unmanned aerial vehicle platform can achieve high-frequency and high-precision inspections of small-scale areas such as parks and forests, and form a collaborative monitoring foundation with satellite-based macroscopic observations for "space-air-ground"; Optical remote sensing uses normalized vegetation index (NDVI) and enhanced vegetation index (EVI) to invert vegetation coverage and growth status. NDVI is suitable for areas with medium to low vegetation coverage, while EVI has higher sensitivity in areas with dense vegetation, providing accurate surface parameters for carbon sink estimation; Thermal infrared remote sensing can capture the thermal radiation intensity and spatial distribution of emission sources, achieving uninterrupted monitoring day and night; SAR technology, with its advantages of penetrating clouds and not being limited by lighting conditions, effectively compensates for the data acquisition shortcomings of optical remote sensing in rainy and low light weather, ensuring the continuity of accounting data.

In terms of core technology adaptation, the CASA model takes photosynthetically active radiation, the fraction of photosynthetically active radiation absorbed by vegetation (fPAR), and light energy utilization rate as core parameters. Due to the easy availability of required parameters and strong regional universality, it has become the mainstream technical method for estimating the net primary productivity (NPP) of terrestrial ecosystem vegetation. Multiple empirical studies on ecosystems such as forests and grasslands in China have shown that the model's simulation results in different climate zones can have a correlation coefficient of 0.6–0.9 with ground observations, accurately capturing the dynamic changes in carbon sinks of different vegetation types under seasonal changes and climate fluctuations. Nighttime Light Remote Sensing (NLRS) relies on the positive correlation between nighttime light intensity and human production and living activity intensity to invert regional carbon emissions. Previous studies have validated DMSP-OLS nighttime light data from 314 provinces and cities in China

from 1992 to 2013, and found that the total amount of light is significantly linearly correlated with CO₂ emissions from fossil fuel combustion ($R=0.91$, $p<0.001$), providing key data support for quickly locating high-emission areas and identifying hotspots of carbon source distribution [3]. These technological features and adaptation advantages complement and work together to enable remote sensing technology to comprehensively cover the entire process of carbon emission accounting, achieving multi-dimensional and uninterrupted data supply from regional macro-scale to local micro-scale, laying a solid foundation for subsequent accurate accounting.

3. The Core Role of Remote Sensing Technology in Whole-Process Accounting

In the carbon source accounting process, remote sensing technology can achieve precise positioning and quantitative accounting of emission sources. For industrial point sources, atmospheric XCO₂ column concentration data obtained through carbon satellites, combined with wind field diffusion parameters observed by meteorological stations, can be used to construct a fitting model that can quickly identify the pollution plume range of large emission sources such as thermal power plants and steel plants, accurately estimate real-time emissions, and improve accounting efficiency by more than 60% compared to traditional manual on-site sampling and monitoring [4]. For transportation carbon emission sources, high-resolution optical remote sensing can accurately extract key parameters such as road traffic flow and vehicle structure. Combined with thermal infrared remote sensing inversion of exhaust emission intensity data and high-precision terrain elevation information obtained by LiDAR, it can effectively capture the impact of terrain differences on carbon emissions. Actual data shows that the carbon emissions per unit mileage on uphill sections of mountainous roads are 15%–30% higher than those on flat roads, and the emission increment margin of heavy-duty trucks is significantly higher than that of light-duty passenger vehicles. In regional carbon emission accounting, scholars such as He Sikai combined NIRS data, population density distribution data, and industrial structure proportion parameters to construct a coupled model [5], generating a high-resolution 1km-scale carbon emission spatial grid, clearly presenting the emission differences of different functional areas in the city, effectively filling the gap in fine-scale carbon emission accounting of urban streets, industrial parks, and other areas. In carbon sequestration accounting, the collaborative application of multi-source remote sensing technology enables accurate estimation of ecosystem carbon sequestration. Optical remote sensing can quickly identify different vegetation types and coverage such as forests, grasslands, and wetlands. LiDAR can obtain three-dimensional structural parameters such as tree crown height and forest density. SAR technology can penetrate cloud layers and vegetation canopies to compensate for the shortcomings of optical remote sensing monitoring under rainy weather. Following the fusion of these three datasets, the combined data is fed into a random forest model to invert regional carbon storage, which can reduce the field investigation cost of forestry carbon sequestration monitoring by more than 70% and reduce the laboratory data processing cycle. In the verification process, remote sensing time-series data can accurately trace the trajectory of land use type changes within a specific period of time, automatically generate verification data packages containing information such as land parcel boundaries, vegetation cover changes, carbon source and sink dynamics, etc., reducing the traditional project verification cycle by nearly half, significantly improving the credibility and authority of accounting results, and avoiding data fraud and carbon fraud in carbon sink project development from a technical perspective.

4. Application Path of Remote Sensing Data Fusion in Whole-Process Accounting

A single remote sensing data source is limited by its own observation characteristics, making it difficult to meet the multidimensional requirements of spatiotemporal resolution, coverage, and accuracy for the entire process of carbon emission accounting. Multi-source remote sensing data fusion has become the core path to improve accounting quality and reliability by constructing a complementary data system [6]. At present, the mainstream fusion models can be divided into two types: "technology-complementary fusion" and "method-collaborative fusion". The former focuses on the complementary advantages of different remote sensing technologies, while the latter focuses on the adaptation and collaboration of accounting methods and data types. At the technical level, the multi-source fusion of optical remote sensing, NIRS, thermal infrared remote sensing, and SAR data can build an all-weather, all-time, high-precision surface monitoring system. For example, in the carbon sequestration accounting of the Yangtze River Delta urban agglomeration, the CASA model integrates optical data from high-resolution satellite series, Sentinel-1 SAR data, and ground meteorological station hourly observation data to achieve precise measurement of carbon sinks at a monthly resolution of 1km, with an accuracy improvement of 23% compared to a single optical data source, effectively avoiding the observation limitations of a single technology.

At the methodological level, the technical path of "tracer gas+main gas" collaborative inversion can solve the technical problems of high background concentration of CO₂ and easy masking of emission signals. NO₂ and CO₂ have strong homology in the combustion process of fossil fuels, and NO₂ has a short lifecycle (only a few hours) and highly distinguishable emission plume signals. The NO₂ plume observed by satellites can cover 92% of CO₂ emissions from fossil fuel combustion. By establishing industry-specific emission ratio (ERs) conversion relationships and dynamically calibrating them in combination with industry emission spectrum characteristics, the accuracy of anthropogenic source CO₂ inversion can be significantly improved [7]. In addition, the deep fusion of remote sensing data and ground measurement data can effectively calibrate inversion errors. In the field of forestry carbon sequestration accounting, coupling LiDAR remote sensing 3D data with ground biomass data can strictly control the estimation error of carbon stocks within 10%, fully meeting the verification accuracy standards of the National Certified Voluntary Emission Reduction (CCER) project; In industrial point source accounting, the fusion of remote sensing inversion data and enterprise online monitoring system (CEMS) data can further improve the accuracy of emission quantification.

5. The Main Challenges of Applying Remote Sensing Technology to Whole-Process Accounting

The limitations of observation conditions are the core technical bottleneck for the application of remote sensing technology in carbon emission accounting, and are constrained by both satellite payload performance and natural environment. Although polar orbit satellites have high spatial resolution ranging from meters to kilometers, their scanning bandwidth is narrow and revisit cycles are often several days, making it difficult to meet the high-frequency monitoring needs for dynamic carbon emission tracing; Geosynchronous orbit satellites can achieve continuous observation at the hourly level, but there is a shortcoming of spatial resolution generally below 10 kilometers, which makes it difficult to accurately capture small and medium-sized emission sources. Meanwhile, natural factors such as cloud cover, aerosol scattering, and atmospheric turbulence interference can lead to a long-term loss rate of 15%–20% in remote sensing data, directly affecting the continuity and accuracy of dynamic

accounting results [8]. In addition, approximately 1.6 billion people worldwide live in areas without nighttime light coverage, which are mostly remote rural or underdeveloped areas with dispersed agricultural and household emissions. Existing remote sensing technology is difficult to accurately quantify their low-intensity and dispersed carbon emissions, resulting in obvious accounting blind spots and a lack of targeted supplementary monitoring methods.

Bottlenecks in methodologies and data have grown increasingly salient, severely hindering the large-scale rollout of this technology. Carbon emission inversion methods suffer from inherent applicability constraints: data-driven inversion is highly reliant on steady-state atmospheric conditions and complete sample datasets, with the error margin rising over 30% in complex terrains such as mountains and river valleys. Model-driven approaches (e.g., WRF-Chem) enable numerical simulation of atmospheric diffusion but entail massive computing power and cumbersome parameter calibration, with simulation uncertainty margins reaching 12%–18% [9]. Inter-sector emission heterogeneity causes significant divergence in NO₂/CO₂ emission ratios (ERs), with the ER gap between thermal power and transportation exceeding a factor of three—no sector-specific unified calibration standards or dynamic correction mechanisms have been established to date. Additionally, remote sensing and traditional statistical data face integration impediments: discrepancies in data formats and accounting calibers, a weak cross-departmental data sharing mechanism, and incomplete historical statistical data together markedly elevate the accounting process complexity and error propagation risks.

6. Practical Strategies for Optimizing Whole-Process Accounting Using Remote Sensing Technology

Aforesaid technological bottlenecks require breakthroughs via the simultaneous advancement of sensor hardware upgrading and inversion algorithm optimization; the timeliness and accuracy of dynamic carbon emission accounting are further improved by accelerating the network deployment and practical use of high-resolution, high-revisit-period remote sensing satellites, with China's Gaofen-5 satellite's EMI sensor realizing kilometer-level precise NO₂ observation and the U.S. TEMPO satellite capturing short-term carbon emission fluctuations through hourly continuous monitoring [10]; It also advances the R&D of hyperspectral sensors and high-sensitivity carbon satellite payloads, and enhances the capability to capture low-concentration emission signals. On the other hand, efforts are being made to optimize the inversion algorithm system, introducing machine learning models such as random forests and neural networks to correct the saturation problem of night light remote sensing data. Domestic research has improved the capture accuracy of low-intensity carbon emissions in unlit areas by 35% through EVI vegetation index correction combined with population weight allocation methods [11], effectively reducing accounting blind spots and decreasing estimation errors of scattered emissions.

Build and improve a standardized system and multi-dimensional data collaboration mechanism to overcome bottleneck constraints in the large-scale technological application, formulate remote sensing accounting technical specifications for key sectors including thermal power, transportation and forestry, clarify sector-specific ER calibration standards, data collection procedures and format requirements, and advance the seamless alignment, integration and two-way verification of remote sensing data with mainstream carbon emission databases such as CEADs and MEIC. Building a space-air-ground integrated monitoring network, addressing the shortcomings of insufficient satellite revisit cycles through high-frequency drone patrols, focusing on strengthening monitoring in small and medium-sized areas such as parks and small watersheds, relying on ground monitoring stations to calibrate remote sensing inversion errors regularly, and forming a multi-scale, full-time data loop. At the same time, lower the technical application threshold by developing lightweight and modular accounting tools, compiling user

manuals, and providing specialized training for grassroots technical personnel to fully adapt remote sensing technology to small and medium-sized carbon sequestration projects and the needs of refined accounting in counties.

7. Conclusion

Remote sensing technology provides a technical solution featuring wide coverage, dynamic monitoring, and high-precision support for the entire process of carbon emission accounting. In key links such as precise carbon source positioning, carbon sink quantitative estimation, and verification of accounting results, it demonstrates technological advantages that traditional accounting methods cannot match, and has become a core supporting means in promoting the "dual carbon" goal. Through multi-source remote sensing data fusion technology, precise carbon emission accounting at the 1km-scale can be achieved. This not only significantly reduces the manpower, material resources, and time costs of on-site monitoring, but also significantly improves the spatiotemporal matching of accounting results, providing reliable data support for carbon quota allocation and emission reduction effectiveness evaluation. However, in practical applications, problems such as limited observation conditions, insufficient adaptability of inversion methods, and weak response to industry emission heterogeneity remain prominent, which hinders the large-scale promotion of technology in small-to-medium-scale application scenarios including counties and industrial parks.

In the future, we need to focus on technological innovation and system construction as the core breakthrough direction, and accurately solve existing application bottlenecks. On the one hand, we will continue to upgrade the hardware performance of remote sensing sensors, optimize inversion algorithm models for complex terrain and low-intensity emission scenarios, and build a space-air-ground integrated monitoring network. Through the three-dimensional collaborative linkage of satellites, drones and ground monitoring stations, observation blind spots are fully eliminated and the accuracy of carbon emission accounting is continuously elevated, while the development of unified technical specifications and the improvement of data collaboration mechanisms are advanced in parallel. Sector-specific remote sensing accounting standards are refined, ERs calibration criteria and data format specifications are standardized, the entrenched barriers to cross-departmental data sharing are dismantled, and remote sensing data is seamlessly aligned and integrated with mainstream carbon emission databases such as CEADs and MEIC. By virtue of technological iterative refinement and large-scale application rollout, remote sensing technology has evolved into a standardized core tool for the full-process carbon emission accounting, which bolsters the scientificity and precision of carbon management practices and furnishes a robust technical underpinning for the implementation of global climate governance initiatives. Going forward, priority should be given to exploring industry-tailored remote sensing accounting solutions, refining the configuration of parameter systems based on the emission characteristics of various sectors, and further enhancing the practicality and operational feasibility of the technology.

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