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Estimation of China's terrestrial ecosystem carbon sink: Methods, progress and prospects

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Abstract China announced its national goal to reach the peak of carbon emission by 2030 and achieve carbon neutrality by 2060, during the General Assembly of the United Nations in September 2020. In this context, the potential of the carbon sink in China's terrestrial ecosystems to mitigate anthropogenic carbon emissions has attracted unprecedented attention from scientific communities, policy makers and the public. Here, we reviewed the assessments on China's terrestrial ecosystem carbon sink, with focus on the principles, frameworks and methods of terrestrial ecosystem carbon sink estimates, as well as the recent progress and existing problems. Looking forward, we identified critical issues for improving the accuracy and precision of China's terrestrial ecosystem carbon sink, in order to serve the more realistic policy making in pathways to achieve carbon neutrality for China.

Keywords Terrestrial ecosystem, Carbon sink, Carbon neutrality, China

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1. Introduction

Terrestrial ecosystems have effectively slowed down climate warming due to its net uptake of atmospheric carbon dioxide (CO_2) over past decades (IPCC, 2013). According to the Global Carbon Project, global terrestrial ecosystems absorbed 31% of anthropogenic CO_2 emissions during 2010–2019 (Friedlingstein et al., 2020). Despite its significant magnitude, the uncertainties of the land carbon sink estimate remain large due to strong heterogeneity of terrestrial ecosystems. Thus, the estimation of global land carbon sink is often based on the residual term of carbon balance equation: the difference between total amount of CO_2 released into the atmosphere by human activities (i.e., CO_2 emissions by fossil fuel combustion and land use change) and the sum of atmospheric CO_2 increment and CO_2 uptake by the ocean. This estimate of the land carbon sink is also known as the residual land carbon sink. This indirect estimation has an advantage in avoiding the difficulties to consider the huge diversity of terrestrial ecosystems. However, since the residual term contains all the errors of other variables in the carbon balance equation, the uncertainty of the estimate is thus larger than the other terms. Moreover, due to the rapid mixing of atmospheric CO_2, this method is only applicable at global scale, rendering the estimate of regional land carbon balance a grand challenge for the scientific community.

Since the 1990s, scientists around the world have conducted many regional studies on land carbon sink, all of which reach a consensus: Northern Hemisphere terrestrial ecosystems are functioning as an important carbon sink, the magnitude of which can roughly offset the imbalance of the global carbon budget, indicating that the puzzle of "missing carbon sink" raised at the end of the last century has been basically resolved (Fan et al., 1998; Pan et al., 2011).

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However, the spatial distribution of the Northern Hemisphere land carbon sink remains uncertain. For example, Fan et al. (1998) estimated the land carbon sink in North America as 1.7±0.5 Pg C yr^{-1} based on an atmospheric inversion model. This was almost equivalent to the size of the land carbon sink over the entire Northern Hemisphere during the same period (Stephens et al., 2007), which has aroused great controversy that many believed the estimate by Fan et al. (1998) overestimated the land carbon sink in North America (Field and Fung, 1999; Holland et al., 1999; Houghton et al., 1999). Similar disputes also occurred in the estimation of the terrestrial ecosystem carbon sink in Europe (Reuter et al., 2017). To better resolve the regional land carbon budgets, a number of regional carbon cycle research projects have been launched worldwide, e.g., North American Carbon Program (NACP), Assessment of the European Terrestrial Carbon Balance-Integrated Project (CARBOEurope-IP), and Carbon Cycle and other GHG gases in Sub-Saharan Africa (CarboAfrica), etc.

In China, with the leadership and support from the Ministry of Science and Technology and the National Natural Science Foundation of China, Chinese scientists have carried out a series of important researches on China's land carbon budgets, whose outcomes have provided critical scientific supports to policy making on achieving carbon neutrality and to China's participation in global climate governance. This paper reviews the contemporary methods for regional land carbon sink estimations, with a focus on the progress and prospects in estimating the land carbon sink in China. Besides these achievements, we also reviewed the sources of considerable uncertainties in China's land carbon sink estimates. We explored the advantages and disadvantages of different methods, clarifying the reasons behind the divergent reports on China's land carbon sink, in order to provide methodology reference and research ideas for more accurate estimates on China's land carbon sink in future.

2. Methods of estimating regional land carbon budget

The methods for estimating the carbon budget of regional terrestrial ecosystems can be divided into two broad categories: the "bottom-up" and the "top-down". The "bottom-up" approach refers to the integration of ground observation and simulation results from sites or grids into a regional estimate. The commonly used "bottom-up" approaches include the inventory method, the eddy covariance method and the ecosystem process modeling method. The "top-down" approach primarily refers to the inversion of terrestrial ecosystem carbon sink based on atmospheric CO_2 concentration, i.e. the atmospheric inversion. Different estimation methods have different strengths, weaknesses and sources of uncertainty, which are reviewed respectively in the following sub-sections.

2.1 Inventory method

The inventory method is based on the comparison of ecosystem carbon stock inventory (mainly vegetation and soil) in different time periods to estimate the carbon budgets of terrestrial ecosystems (Dixon et al., 1994; Fang et al., 2001; Piao et al., 2009; Pan et al., 2011). For example, utilizing the continuous forest resource inventory data, Fang et al. (2001) estimated China's forest biomass carbon stock change through multiplying the timber volume change with a biomass expansion factor (BEF) (Fang et al., 2001). For ecosystem types that lack continuous inventory data, such as shrub and grassland, an empirical relationship between observed vegetation carbon stock and remotely sensed vegetation indices can be established to estimate vegetation carbon stock changes (Piao et al., 2009). For a similar reasoning, the soil inventory and field measurements in different periods were also used to estimate the changes of soil carbon stock. Thus, the terrestrial ecosystem carbon budgets based on the inventory method can be obtained by combining the estimated changes of vegetation and soil carbon stock at the same periods.

The main advantage of the inventory method is that it is based on the direct measurements of carbon stock of vegetation and soil at the site scale. However, there are several limitations to this method: (1) The revisiting cycle of carbon stock inventory is usually 5 years or even longer, and the spatial resolution is typically administrative units. The low temporal and spatial resolution make it difficult to accurately depict the inter-annual variation and fine spatial pattern of carbon budgets. (2) The inventory data is spatially biased towards more widely distributed ecosystems, such as forests and grasslands. The long-term inventory data are scarce for wetlands and other ecosystems with a low proportion of land area, which unavoidably leads to some biases in regional land carbon budget estimates. (3) Due to the huge spatial heterogeneity of terrestrial ecosystems, the scaling-up from site-scale measurements to regional scale estimates embedded considerable uncertainties. (4) Contemporary inventory data do not include lateral carbon transport, such as carbon in wood products and organic carbon transferred with soil erosion. Thus, the coverage of carbon stock types and sampling density are the key factors in accurate estimate of land carbon sink based on inventory method.

2.2 Eddy covariance method

Eddy covariance directly measures the net CO_2 exchange between terrestrial ecosystems and the atmosphere within its footprint area (usually several square meters to several square kilometers), based on the principle of micrometeorology. These measurements were then scaled-up to regional net ecosystem productivity (NEP) (Jung et al., 2011; Yu et al., 2014a; Wang et al., 2015; Yao et al., 2018a). The main advantage of the eddy covariance method is continuous in-situ measurement of ecosystem carbon flux at fine time scale (e.g., every half hour), which reflects the impact of climate fluctuations on NEP (Yu et al., 2014b). Limitations of eddy covariance method includes: (1) Since it is based on the principle of micrometeorology, eddy covariance measurements were inevitably affected by measurement and representative errors due to missing observation, complicated underlying surface and meteorological conditions, energy balance closure issues, occasional instrument errors. (2) Flux sites in forest ecosystems are often located in areas with minor human disturbances, making it difficult to take the forest age difference and ecosystem heterogeneity into account, which further lead to biases when measured fluxes are scaled up to regional scale. (3) The eddy covariance measurements cannot distinguish the carbon budgets of soil from above and below-ground biomasses, which make it impossible to estimate the agricultural ecosystem carbon budget. (4) The potential source of biases at regional scale also includes the disturbances such as logging, fire and land cover change, the neglection of which could also lead to overestimates in the regional ecosystem carbon sink (Jung et al., 2011). For example, based on scaled-up eddy covariance measurements, Jung et al. (2011) estimated the global NEP to be 23 Pg C yr^{-1}, which was about 8 times the global land carbon sink (Jung et al., 2011). Overall, the eddy covariance method is rarely used to estimate the size of the carbon sink at the regional scale, mostly due to lack of consideration on widespread human disturbance and managements of ecosystems. It is more widely used to understand the response of the carbon cycle to climate change at the ecosystem scale.

2.3 Ecosystem process modeling method

Process-based ecosystem models provide gridded carbon flux estimates by simulating the processes and mechanisms of the terrestrial ecosystem carbon cycle. These models have become an important tool for many global and regional terrestrial ecosystem carbon sink assessments, including the Global Carbon Project (Friedlingstein et al., 2020). The main advantage of process modeling is that it can quantitatively partition the contribution of different driving factors to the change of terrestrial carbon sink, and can project their future changes (Sitch et al., 2008; Piao et al., 2017). Its limitations mainly include: (1) There are still large uncertainties in the model structure, parameters and driving factors (such as climate and land use change data, etc.). (2) The impacts of ecosystem managements (such as forest management and agricultural irrigation, etc.) on the carbon cycle were neglected or oversimplified in contemporary process models (Piao et al., 2018). (3) Most models do not account non-CO_2 carbon emissions (e.g., biogenic volatile organic compounds) or lateral carbon transport such as riverine carbon processes (Regnier et al., 2013). Due to the significant differences in structure, parameters and driving factors of different process models, multi-model comparison projects, including TRENDY, MsTMIP and ISIMIP, show that there are still great uncertainties, which brings controversies to the reliability of simulated carbon sink at regional scales (IPCC, 2013).

2.4 Atmospheric inversion method

Atmospheric inversion estimates the land carbon sink based on atmospheric transport model and measurements of atmospheric CO_2 mole fraction, combined with anthropogenic CO_2 emission inventory (Bousquet et al., 2000; Gurney et al., 2002). Different from the "bottom-up" approach, atmospheric inversion has the advantage of near-real-time assessments on land carbon sink and its response to climate change at a global scale. The limitations of atmospheric inversion include: (1) The spatial resolution of net carbon flux data derived from atmospheric inversion is low at present, which cannot accurately partition the carbon fluxes of different types of ecosystems. (2) The accuracy of inversion estimates is limited by the number and distributions of atmospheric CO_2 observation sites (the ground CO_2 mole fraction observation sites are mainly distributed in North America and Europe, but are very limited in developing countries), the uncertainties of the atmospheric transport model and the CO_2 emission inventories (such as fossil fuel combustion emissions). (3) The atmospheric inversion generally does not consider the carbon exchange between land and atmosphere in non-CO_2 forms, as well as the transfer of carbon emissions caused by international trade. In general, the smaller the target regions, the larger the uncertainties of atmospheric inversion (Peylin et al., 2013). At national scales, even in Europe and America with many atmospheric CO_2 observation sites, the uncertainty of atmospheric inversion results remains non-negligible.

3. Progress in estimating China's land carbon sink

3.1 The size of China's land carbon sink

As mentioned above, Chinese scientists have employed a variety of methods to estimate China's land carbon sink over the past 20 years, of which the results can be summarized in Figure 1. These studies showed that China's terrestrial ecosystem was an important carbon sink, but there was a divergence among the estimations of different methods. The inventory method estimated that China's terrestrial carbon sink was 0.21–0.33 Pg C yr^{-1} (after adjusting the amount of carbon deposition in inland water −0.02 Pg C yr^{-1}; Jiang et al., 2016), which was comparable with the estimates of ecosystem process models (0.12–0.26 Pg C yr^{-1}) (Figure 1a). However, great uncertainties (0.17–1.11 Pg C yr^{-1}) by up to an order of magnitude were found among different atmospheric inversions. In particular, Wang J et al. (2020) reported that China's terrestrial carbon sink was 1.11±0.38 Pg C yr^{-1}, which was equivalent to 60% of the global terrestrial carbon sink during the same period. This was not only higher than the results estimated by other methods, but also much larger than other atmospheric inversion estimates. This estimate was so controversial that Chen et al. (2021) adopted basically the same atmospheric CO_2 concentration observation data as Wang J et al. (2020) (except Hong Kong observation station), but different atmospheric inversion models (CTC-5) so as to re-estimate the terrestrial carbon sink. As a result, Chen et al. (2021) found that China's land carbon sink was 0.45 Pg C yr^{-1} (carbon transfer from wood and food international trade and non-CO_2 carbon emissions were not adjusted), which was only 41% of the estimation by Wang J et al. (2020). In general, with the exception of Wang J et al. (2020), after adjusting the carbon emissions transferred from international trade of wood and food and non-CO_2 carbon emissions (~0.14 Pg C yr^{-1}) (Wang et al., 2021), the estimated China's land carbon sink based on the atmospheric inversion model was 0.17–0.35 Pg C yr^{-1} (Figure 1a), which is generally consistent with the "bottom-up" inventory method.

Through the comparison of the carbon sink size of China's terrestrial ecosystems estimated by the above different methods, we found that there were much greater uncertainties in the estimated results from different inversion models than other methods. Therefore, using estimates from a single atmospheric inversion model should be viewed with caution, and further check them with ground observations. We noticed that the issues of overestimating the size of regional carbon sinks by atmospheric inversions has also occurred in North American and European studies (Fan et al., 1998; Reuter et al., 2017), which further illustrated the necessity to jointly use atmospheric inversion and "bottom-up" methods to constrain the land carbon sink estimates. In addition, recent studies pointed out the other reason for Wang J et al. (2020) to overestimate China's land carbon sink was that they used the CO_2 concentration data from Shangri-La Observatory in low-resolution atmospheric inversion. The Shangri-La observation station was located in Hengduan Mountains with complex topography, and there was a significant bias (Wang et al., 2021) in representing atmospheric

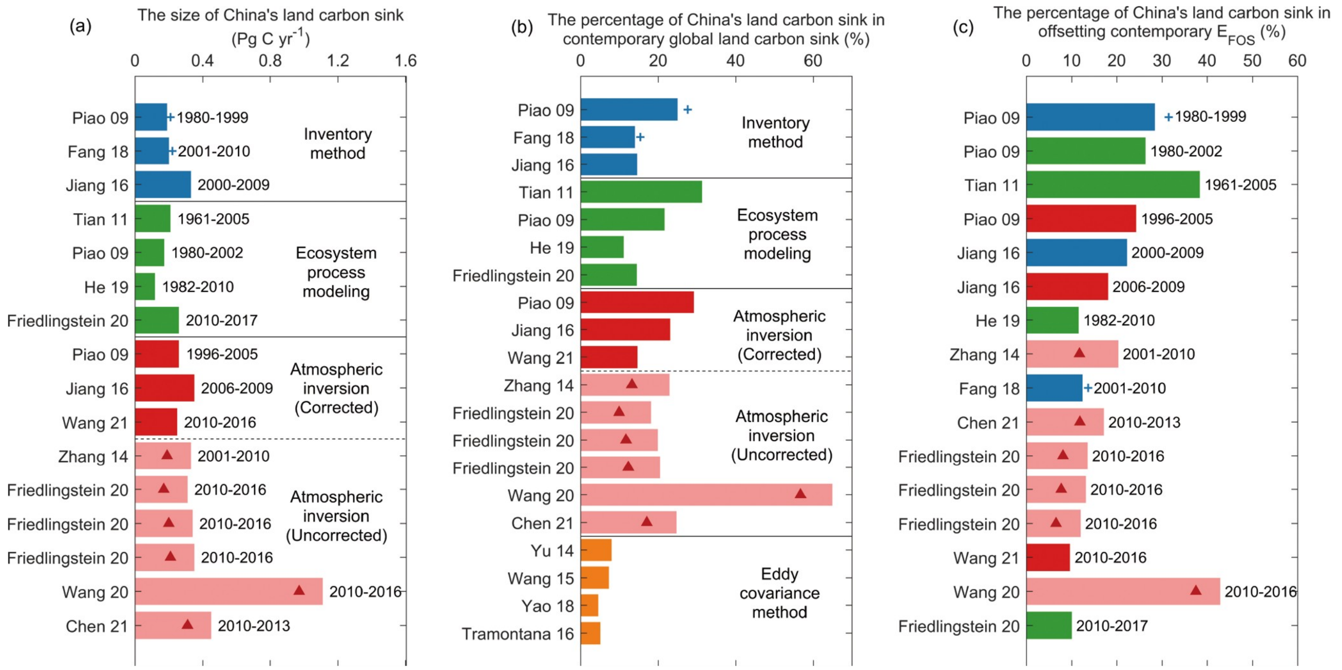

Figure 1 The size of carbon sink in China's terrestrial ecosystems estimated by different methods. (a) The size of China's land carbon sink. Blue, green and red (both dark and light red) bars represent the carbon sink size estimated based on the inventory method, the ecosystem process modeling method and the atmospheric inversion method, respectively. The blue cross represents the estimate after considering the carbon deposition in inland water in the inventory method. The light red bars represent the estimate of the atmospheric inversions not corrected for lateral fluxes and non-CO_2 carbon emissions, while the red triangles represent the corresponding estimates after correcting for lateral fluxes and non-CO_2 carbon emissions. (b) The percentage of China's land carbon sink in contemporary global land carbon sink. Orange bars represent the global share of net ecosystem productivity (NEP) estimated based on the eddy covariance data. (c) The percentage of China's land carbon sink in offsetting contemporary fossil fuel CO_2 emissions (E_{FOS}). Both China's E_{FOS} and global net land carbon sink data come from the annual assessment report of Global Carbon Project (Friedlingstein et al., 2020). Note that the studies in (c) are re-ordered according to the study periods.

Table 1 The advantages and disadvantages of different methods for estimating terrestrial ecosystem carbon sink

Estimation methods		Advantages	Disadvantages
Bottom-up	Inventory method	More accurate in vegetation and soil carbon stock in sampling sites	(1) Long revisiting time and low spatial resolution; (2) missing some ecosystem types, such as wetlands; (3) large uncertainty in scaled-up to regional scale; (4) lateral transport of carbon is neglected
	Eddy covariance method	Long-term continuous in-situ measurements of ecosystem carbon flux at fine time scale, and conductive to understanding the mechanisms of carbon cycle response to environmental change	(1) Missing observations, complicated terrain and meteorological conditions, unclosed energy balance and systematic error of observation instruments; (2) difficulty to take the ecosystem heterogeneity into account, little human disturbance at the observation sites; (3) incapability to partition carbon flux components such as harvest and soil fluxes in agriculture ecosystem; (4) overestimating the ecosystem carbon sink at regional scale due to neglecting the effects of logging, fire and other disturbances
	Ecosystem process modeling method	To quantitatively partition the contribution of different driving factors to the change of terrestrial carbon sink, and project future changes of land carbon sinks	(1) Uncertainties in model structure and parameters; (2) the impact of ecosystem management on carbon cycle are commonly neglected or oversimplified; (3) non-CO_2 carbon emissions and lateral carbon transport processes such as river transportation are not included in most models
Top-down	Atmospheric inversion method	To estimate near-real-time change of carbon source and sink at global scale	(1) Carbon fluxes of different ecosystem types cannot be accurately partitioned due to low spatial resolution; (2) the accuracy of inversion is limited by the number and distribution of atmospheric CO_2 observation sites, the uncertainties of atmospheric transport model and CO_2 emission inventory; (3) the non-CO_2 land-atmosphere carbon exchange and carbon emission transfer caused by international trade are generally not considered

CO_2 concentration of a grid (4°×5°) in the coarse resolution inversion model that the concentration difference could be up to 5 ppm. This representation error was large enough to significantly affect the atmospheric inversion estimates. After excluding Shangri-La station data, the French Atmospheric Inversion Model (CAMS) estimated the size of China's land carbon sink to be 0.25 Pg C yr^{-1}, which was 50% lower than before (Wang et al., 2021) and close to other methods. Therefore, the rational selection and deployment of atmospheric CO_2 observation stations was also the key to accurately estimate regional land carbon sink using atmospheric inversions.

3.2 The share of China in the global land carbon sink

Based on our review of China's land carbon sink estimates, we found that China, with approximately 6.5% of the world's land area, contributed 10–31% of the global land carbon sink (Figure 1b, excluding Wang J et al. (2020)), indicating that China's terrestrial ecosystems played an important role in the global land carbon sink. Compared with other regions, the total carbon sink of China's terrestrial ecosystems was comparable to Europe (0.14–0.23 Pg C yr^{-1}) (Janssens et al., 2003; Ciais et al., 2006, 2020), but less than the United States (0.30–0.58 Pg C yr^{-1}) (Pacala et al., 2001; King et al., 2015). In terms of carbon sink intensity, China's terrestrial ecosystem (18–37 g C m^{-2} yr^{-1}) was similar to Europe (16–26 g C m^{-2} yr^{-1}). It should be noted that although the carbon sink intensity of forest ecosystems in China and the United States was similar (1.22 vs. 0.94 Mg C ha^{-1} yr^{-1}; Pan et al., 2011), the proportion of desert and bare land in China was much larger than that in the United States. As a result, China's land carbon sink intensity was about half than that in the United States (33–63 g C m^{-2} yr^{-1}).

Interestingly, unlike other methods, the eddy covariance method estimated that China's net ecosystem productivity (NEP) accounted for only 5–8% of world's total (Yu et al., 2014a; Wang et al., 2015; Tramontana et al., 2016; Yao et al., 2018a), which was much lower than the global share of China's land carbon sink as summarized in Figure 1. This is because the NEP estimated by eddy covariance methods at regional scale should not be viewed as equivalent to carbon sinks, because the former did not account carbon fluxes caused by ecosystem disturbances and managements. Therefore, comparing the significant difference between China's terrestrial ecosystem NEP and its global share of carbon sink further reveals that ecological projects, such as afforestation, and ecosystem management contributed more to China's ecosystem carbon sinks than the global average. At the same time, as China's plantation was currently dominated by young and middle age forests (Zhang et al., 2017), they possessed greater carbon sink potential than old forests. Therefore, compared with Europe and the United States, China's forest ecosystems would have a greater potential for acting as a carbon sink in the future, whose specific size and distribution, however, need to be further studied in future.

3.3 China's land carbon sink partly offsets its contemporary fossil fuel CO_2 emissions

The significant carbon sink in China's terrestrial ecosystems has effectively offset part of China's fossil fuel emissions (Figure 1c). However, it is noticeable that since the 1980s, China's total fossil fuel emissions have increased by an average of 15% per year (Friedlingstein et al., 2020), leading to a continuous decline in the proportion of China's fossil fuel emission offset by contemporary land carbon sink (Figure 1c), from −30% in the 1980s and 1990s to 7–15% since 2010. This suggest that although afforestation and other ecological projects enhanced land carbon sink and thus could alleviate the country's pressure of emission reduction, the growth rate of carbon sink (Figure 1a) was much lower than that of fossil fuel emissions. We further expected that as the proportion of mature and old forests in China increases in the future, the proportion of fossil fuel CO_2 emission offset by land carbon sink would further decline since the forest carbon sink intensity decreases with the increase of forest age. Thus, the integrated application of emission reduction measures is the necessary pathway for China to achieve the carbon neutrality.

4. Future perspectives

To achieve carbon sink accounting in a "measurable, reportable and verifiable" manner is an important scientific basis for China's policy making in emission reduction and sink enhancement. To efficiently and effectively meet these requirements is both a challenge and an opportunity for the scientific community. As reviewed above, great uncertainties remain in accounting China's land carbon sink due to methodological differences in estimating regional carbon budgets. At present, estimating China's land carbon sink mainly relies on these four methods, which are respectively improving with emerging new observations, strengthening computational powers and developing algorithms. In addition, the uncertainty assessment is one of the grand challenges at present due to the multiple scales and sources of uncertainties concerned. As the pros and cons of these methods are complementary, we proposed that an integrated "ground-air-space" carbon accounting system (Figure 2) utilizing "multiple data, processes, scales and methods" is required for better accounting the carbon budgets of China's terrestrial ecosystems. To this end, future works should be strengthened in the following aspects:

4.1 Filling the observational gaps and establishing a standard national observation system

For decades, Chinese scientists have conducted a large number of observational studies on the carbon stocks of China's terrestrial ecosystems, and lay a solid foundation for understanding the status of the carbon sinks and its potentials. However, due to the diversities and heterogeneities of China's terrestrial ecosystems, contemporary observations remain insufficient. The following three aspects of limitations need to be addressed.

First, observation of belowground carbon pool, especially soil carbon pool needs to be strengthened. At present, the inventory of aboveground vegetation is well developed in China, and it has been further improved through emerging remote sensing technologies to estimate its change at different spatial and temporal scales. However, periodical and standardized inventory of soil carbon stock is still lacking at national scale, especially in the central and western regions. For example, estimates of the carbon pool in the 0–3 m deep permafrost on the Tibetan Plateau varied by more than a fold in different studies (Ding et al., 2019; Wang T H et al., 2020). To accurately estimate the soil carbon stock and its changes in China, a standardized and comprehensive soil inventory should be carried out regularly.

Second, observation in wetlands, deserts and other ecosystems sensitive to climate change needs to be strengthened. Previous carbon cycle observations mainly focused on forests and grasslands, while other ecosystems, such as wetlands and deserts, still has a non-negligible role in the national carbon budgets. For example, the soil carbon accumulation rate of Zoige Wetland has reached 5–48 g C m^{-2} yr^{-1} since the Holocene, with a significant carbon sink potential (Chen et al., 2014). It should be noted that ecosystem carbon stock consists of both organic and inorganic carbon stocks. In the desert area of northwest China, saline soil water dissolves and absorbs CO_2, and thus forms an inorganic carbon sink. This abiotic carbon fixation potential cannot be neglected, given the vast desert area in China (Li et al., 2015). However, in recent years, factors such as nitrogen deposition and climate change can lead to a large loss of soil inorganic carbon in China (Raza et al., 2020; Song et al., 2022). Taken together, the sparse observations available in the desert ecosystems is a critical gap that needs to be filled.

Third, observations on human disturbances of the ecosystems needs to be improved. Ecosystem observation sites were often built in ecosystems with little human disturbance. However, human footprint (including disturbance and ecosystem management) have exerted significant impacts on the regional carbon balances. For example, China's afforestation contributed 25% of the global increase in greening (Chen et al., 2019; Piao et al., 2020a), however, a recent study found that whether afforestation increases soil carbon stocks varied from place to place and was significantly affected by tree species and pre-afforestation soil stocks and properties (Hong et al., 2020). In the alpine grassland of the Qinghai-Tibet Plateau, grazing and fencing are important factor for the carbon balance that the years of fencing significantly affected grassland carbon sequestration (Sun et al., 2020). The role of human footprint on terrestrial ecosystem carbon

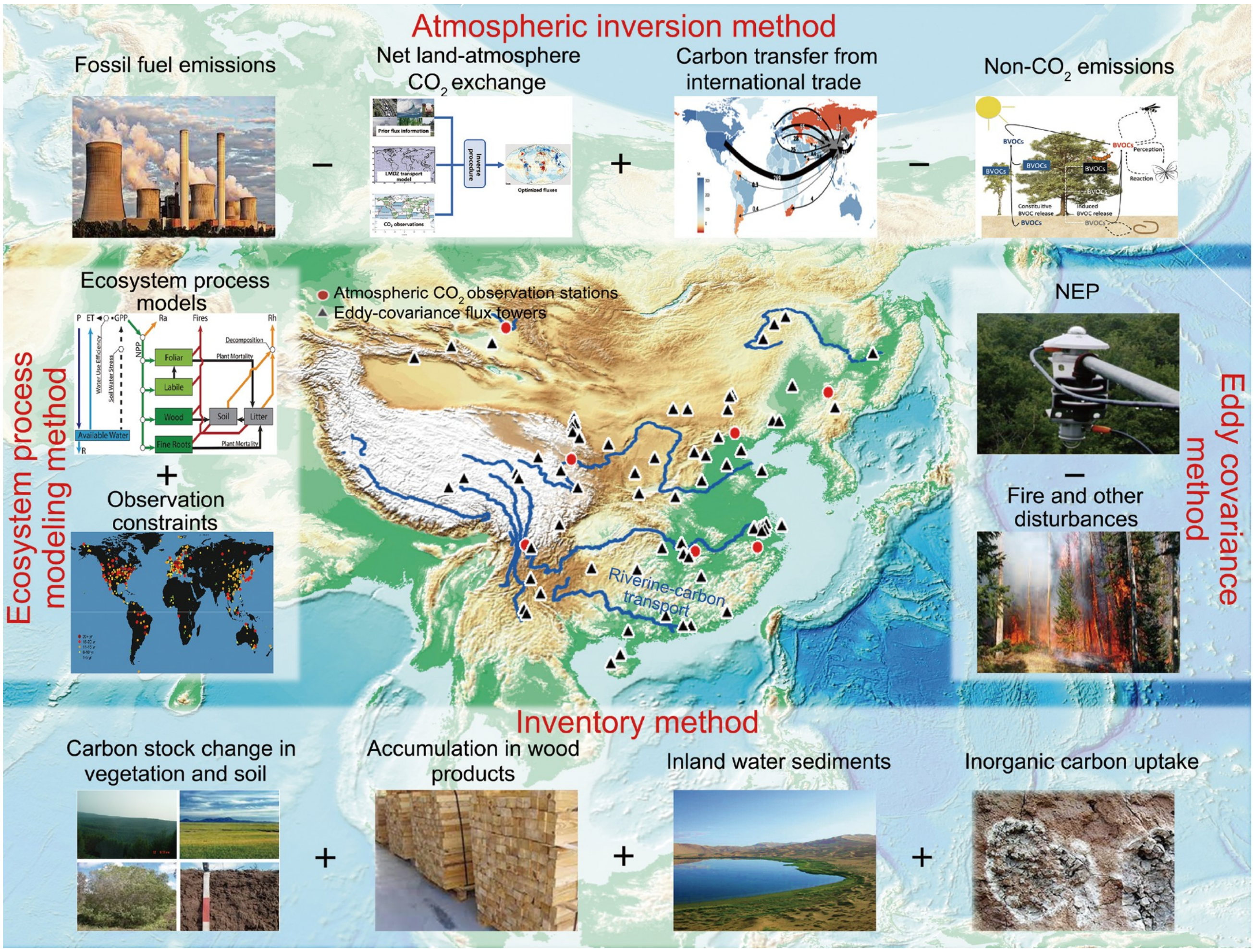

Figure 2 A diagram of an integrated observation and assessment system for China's land carbon sink. The locations of terrestrial ecosystem eddy-covariance flux towers (ChinaFlux) are indicated by grey triangles (www.chinaflux.org), and the atmospheric CO_2 observation stations are indicated by red dots. The diagram illustrates the monitoring and assessment of China's land carbon sink by a variety of methods (inventory method, eddy covariance method, ecosystem process modeling method and atmospheric inversion method), through the utilization of "multiple data, processes, scales and methods" to harness the advantages of different methods and observation platforms, within the integration of "ground-air-space" carbon accounting system.

balance remains elusive at national scale. In particular, the observations of lateral carbon transport and change of organic carbon caused by forest cutting and livestock grazing need to be enhanced urgently.

4.2 Improving remote sensing based atmospheric CO_2 observations and CO_2 tracer observations, as well as establishing a synergistic inversion system for China's terrestrial ecosystem carbon budget and fossil fuel carbon emissions

Atmospheric inversion is not only important to estimate the ecosystem carbon budget, but also key to evaluate the effects of emission reduction. The 2019 revision of 2006 IPCC Guidelines for National Greenhouse Gas Inventories specified that the satellite remote sensing, in-situ CO_2 observation, and atmospheric inversion systems should be used for estimating greenhouse gas emissions, as independent verifications of traditional "bottom-up" inventory. In order to realize the near-real-time and high-resolution CO_2 concentration observation and flux inversions, the United States and Europe have proposed the blueprints for a new generation comprehensive CO_2 inversion system, but China's capacity in this aspect needs to be strengthened.

At present, the bottleneck of accurate atmospheric inversion on China's land carbon sink is the scarcity of long-term atmospheric CO_2 concentration observation data (Wang et al., 2021), let alone assessing the provincial carbon budget with high spatial resolution. Therefore, it is imperative to expand the ground CO_2 observation network. In order to construct such a network in a scientific and efficient manner, it is necessary to assess the efficiency of potential site locations by tracking CO_2 based on the atmospheric transport model, and to evaluate whether the observed data reduce the uncertainty of regional carbon budget estimation effectively based on the atmospheric inversion model, so as to construct a cost-effective observation network. In the meantime, well developed satellite remote sensing CO_2 column concentration data can become a supplementary data source to fill the gap of ground CO_2 observation. Unfortunately, remote sensing CO_2 observation has not yet played its role in China's inversion estimates of China's land carbon sink. So far, China only has one scientific observation satellite (TANSat) designated for the column concentration monitoring of greenhouse gases, and few other satellites (Fengyun3D and Gaofen-5) could be used for inverting atmospheric CO_2 column concentration as well. Therefore, in the future, it is necessary to invent a new generation of domestic satellites for greenhouse gas concentrations with high spatial and temporal resolution, and establish high-resolution radiation transfer models and molecular spectroscopy database to improve the accuracy of CO_2 column concentration observations, and to enhance the inversion capability of China's land carbon sink effectively.

On the other hand, traditional atmospheric inversion is only for the land-atmosphere net carbon flux, and lack corresponding observational constraints on fossil fuel emissions, whose estimates relies solely on fossil fuel emission inventories. However, there are large uncertainties in the current fossil fuel emission inventory at regional and urban scales, further leading to inaccurate inversion estimates of ecosystem carbon sink (Chevallier et al., 2019). Recent studies have shown that fossil fuel carbon emissions and ecosystem carbon budgets can be effectively distinguished by combining the measurements of the isotopic composition of atmospheric CO_2 (^{13}C and ^{14}C) and carbonyl sulfide (COS) (Keeling et al., 2017; Campbell et al., 2017; Basu et al., 2020). Therefore, a synergic observation network of atmospheric CO_2 concentration, carbon isotope and carbonyl sulfide, comprehensive inversion model based on high-resolution remote sensing and ground-based multi-species observation, and inversion system of terrestrial ecosystem carbon budget and fossil fuel emissions are needed to realize regional and provincial emission monitoring. The inversion system can serve for the effectiveness evaluation of the Paris Agreement, provide China's national data and solutions for global and regional carbon budget assessment, and further promote international cooperation on emission reduction and carbon sink enhancement.

4.3 Developing the human-natural coupled terrestrial ecosystem carbon cycle process model to improve the projection on stability of China's land carbon sink

Process-based ecosystem carbon cycle models are important tools for projecting future changes in land carbon sinks. More than a dozen different models were widely used in the Global Carbon Project and IPCC assessments of the global carbon budget. However, there is no carbon cycle model with the full intellectual properties owned by domestic institutes that has occupied an important position in the frontier research of global terrestrial carbon cycling. One important reason is that we have a late start in this field and the research foundation is relatively weak. It is urgent to strengthen the developments of ecosystem carbon cycle models.

A potential breakthrough in the development of ecosystem carbon cycle models with Chinese characteristics is to integrate the process of human activities into the models. After more than 30 years of development, mainstream carbon cycle models in the world have been able to simulate the response of natural carbon cycle to climate change in a relatively mature way (Fisher and Koven, 2020; Friedlingstein et al., 2020), but the impacts of human activities on ecosystems was generally not well depicted (Bonan and Doney, 2018). For example, only a few models could describe the impacts of forest managements on ecosystem carbon sources and sinks (Pugh et al., 2019); Most models did not consider the effects of lateral transport of organic carbon (Ciais et al., 2021), forest age (Yao et al., 2018b) and agricultural ecosystem management (Le Quéré et al., 2018) on the land carbon sink. Models that can simultaneously simulate those processes have not seen reported. Considering that the carbon sequestration of China's terrestrial ecosystems in the past decades was largely due to ecological projects such as the "Grain for Green" project (Lu et al., 2018), it is crucial to develop human-natural coupled ecosystem carbon cycle models to accurately project the carbon sequestration potential of China's terrestrial ecosystems (Fu, 2018).

On the other hand, observations showed that the stability of terrestrial ecosystem carbon sinks was relatively weak (Piao et al., 2020b). For example, extreme climate events led to the release of large amounts of CO_2 from ecosystems, which could offset completely or partially the net carbon uptake accumulated by ecosystems at the regional scale over years (Ciais et al., 2005; Piao et al., 2019). However, current models could not accurately diagnose the response of ecosystem carbon sinks to extreme climate events, especially its vulnerability under the extreme climate events (Schewe et al., 2019). Estimating the stability of ecosystem carbon sink, especially in the regions sensitive to climate change, fragile ecosystems, or hotspots of carbon sinks (such as the Qinghai-Tibet Plateau, Loess Plateau and Southwest Karst Region of China), is very important for accurately projecting the changes of China's land carbon sinks and improving ecosystem managements. These are also major weaknesses in the current model development. Therefore, it is urgent to improve ecosystem response to extreme climate events and frozen soil's freezing-thawing processes in the human-natural coupled ecosystem process model, and to establish carbon cycle parameters and databases for different ecosystems in China, in order to improve the simulation accuracy and spatial-temporal resolution.

5. Conclusion

Revealing the size of China's land carbon sink is of great significance for realizing the national carbon neutrality goal. This paper reviewed the uncertainties in the size of China's land carbon sink. We further summarized the progress of carbon budget estimation, and explained methodological reasons behind the uncertainties. Overall, taking state-of-the-art results into account, we concluded that China's terrestrial ecosystem is an important carbon sink, with the average value calculated by different methods of 0.24 Pg C yr^{-1} (ranging from 0.17 to 0.35 Pg C yr^{-1}). Due to the rapid increase in China's total fossil fuel emissions, the proportion of fossil fuel carbon emissions offset by the contemporary land carbon sink has been declining, from ~30% in the 1980s and 1990s to 7–15% since 2010. Future researches should combine "multiple data, processes, scales and methods" to build an integrated "ground-air-space" carbon accounting system for China, and establish a decision support system for carbon sink management to provide scientific supports for achieving China's carbon neutral goal in 2060.

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