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The greenhouse gas budget for China's terrestrial ecosystems

Xuhui Wang [1,*], Yuanyi Gao [1], Kai Wang [1], Yuxing Sang [1], Yilong Wang [2], Yuzhong Zhang [3,4], Songbai Hong [1], Yao Zhang [1] and Wenping Yuan [5]

The increased atmospheric concentrations of greenhouse gases (GHGs, including CO_2, CH_4 and N_2O) are unequivocally the major driving forces of climate warming [1]. These GHGs originate not only from the use of fossil fuels, but also from disturbances to and management of terrestrial ecosystems. Recent evidence suggests that terrestrial ecosystems, including various land ecosystems and inland water bodies, have become a net source of GHGs [2]. Reducing these ecosystem GHG emissions is therefore of immense importance for climate change mitigation [3]. Indeed, ecosystem GHG emission reduction is also a key component of the recently emerging natural climate solutions (NCS), which have attracted particular interest in China [4]. However, the lack of a comprehensive understanding of China's GHG budget has hindered proper assessment and large-scale application of NCS, impeding the nation's ambition to achieve carbon and eventually climate neutrality. To fill this crucial knowledge gap, here we provide a comprehensive GHG budget of China during the 2000s and 2010s with the dual constraint approach from both the bottom-up estimates (based on ground inventories and biogeochemical models) and the top-down estimates (based on atmospheric inversions).

We conducted a thorough GHG budget assessment over China, encompassing ∼40 budget terms. Details of the assessment framework can be found in [5], which aligns consistently with the methodology and terms used by the Global Carbon Project [6]. Specifically, for the bottom-up estimate, we gathered data from 31 ground inventories (11 for CO_2, 10 for CH_4 and 10 for N_2O, respectively) and 48 biogeochemical models (18 for CO_2, 23 for CH_4 and 7 for N_2O, respectively). Meanwhile, the top-down estimate involved 17 atmospheric inversions (10 for CO_2, 3 for CH_4 and 4 for N_2O, respectively). By utilizing this multi-model and multi-data-source approach, we are able to provide a comprehensive assessment for all GHG fluxes of terrestrial ecosystems in China, while substantially minimizing the potential risk of a single biased model/flux source on the overall GHG budget. To assess the overall greenhouse effect, our budget combines CH_4 and N_2O with CO_2, based on greenhouse warming potential (GWP, in CO_2 equivalent) at the 100-year horizon [1]. GWP measures the cumulative impacts that the emission of 1 g of greenhouse gas could have on the planetary energy budget relative to 1 g of reference CO_2, which mainly depends on the molecular structure and the lifetime in the atmosphere [2] (see also Supplementary Methods).

According to our best estimate, China's terrestrial ecosystems act as a small GHG sink (–29.0 ± 207.2 Tg CO_2-eq yr^{-1} with the bottom-up estimate and –75.3 ± 496.8 Tg CO_2-eq yr^{-1} with the top-down estimate; Fig. 1). By contrast, global terrestrial ecosystems in general release more GHG into the atmosphere than they absorb [2]. When differentiating terrestrial ecosystems into natural ecosystems and agricultural ecosystems using the bottom-up estimate, we find a much larger net sink of GHGs in China's natural ecosystems (–838.4 ± 167.0 Tg CO_2-eq yr^{-1}; Supplementary Table S1), which, however, is largely cancelled out by GHG emissions from agricultural ecosystems. Hence, reducing GHG emissions from agricultural ecosystems should be the priority for increasing the overall net GHG sink of terrestrial ecosystems in China. Furthermore, the small net sink of GHGs is also a result of a larger net CO_2 sink, offset by net sources of CH_4 and N_2O (Supplementary Table S2).

China's terrestrial ecosystems are a significant net CO_2 sink (–1151.0 ± 425.1 Tg CO_2 yr^{-1} with the top-down estimate and –1229.2 ± 149.1 Tg CO_2 yr^{-1} with the bottom-up estimate). It is also noteworthy that, with lateral flux adjustments, the top-down and bottom-up estimates of the CO_2 budget show only a 6% difference, demonstrating recent methodological progress [7]. This convergence instills confidence in the accuracy of forthcoming CO_2 stocktake assessments under the United Nations Framework Convention for Climate Change. Furthermore, China's land ecosystem CO_2 sink contributes ∼20% to the contemporary global land CO_2 sink despite occupying only 7% of the global land area [8]. More than half of China's terrestrial ecosystem CO_2 sink is attributed to forest ecosystems (Supplementary Table S2), primarily due to large-scale afforestation and reforestation efforts.

Regarding CH_4, terrestrial ecosystems in China are a net source of methane emissions (26.1 ± 4.4 Tg CH_4 yr^{-1} with the bottom-up estimate and 26.4 ± 5.6

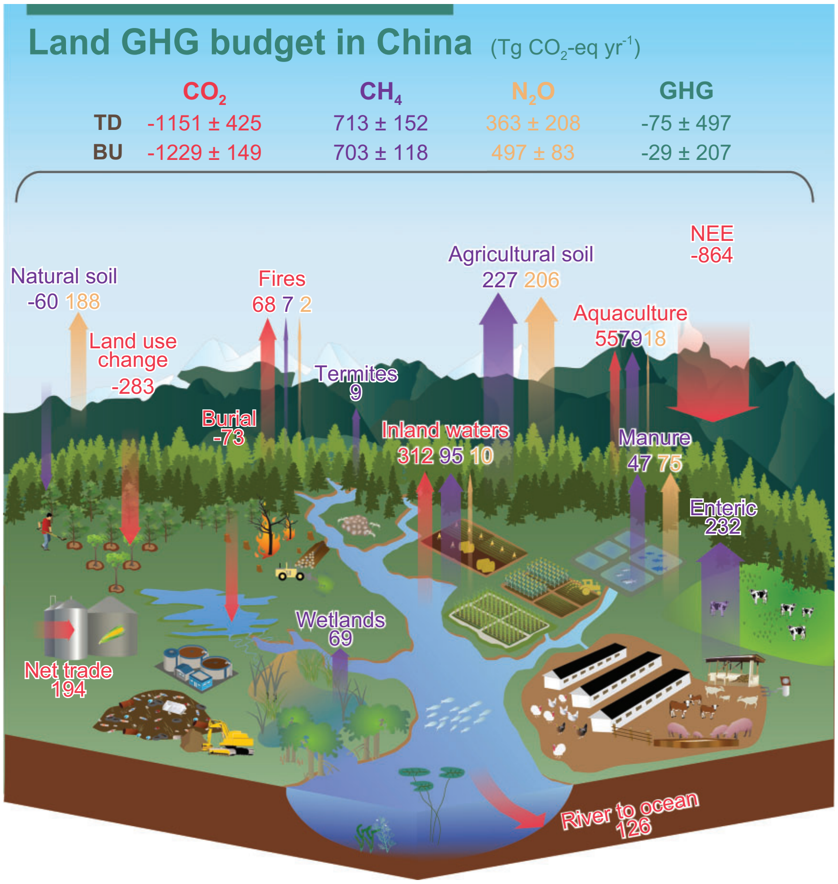

Figure 1. The greenhouse gas (GHG) budget for China's terrestrial ecosystems during the 2000s and 2010s.

Tg CH_4 yr^{-1} with the top-down estimate). The primary contributors to these CH_4 emissions are enteric fermentation and paddy rice cultivation, accounting for ∼60% of the net CH_4 source (Fig. 1 and Supplementary Table S2). Only non-saturated natural soil acts as a sink for CH_4 at –2.2 ± 0.2 Tg CH_4 yr^{-1}.

Similarly, China's terrestrial ecosystems are also a net source of N_2O (1.8 ± 0.3 Tg N_2O yr^{-1} with the bottom-up estimate and 1.3 ± 0.8 Tg N_2O yr^{-1} with the top-down estimate). N_2O also exhibits the largest relative difference between the top-down and bottom-up estimates (∼25%) among the three GHGs, probably resulting from the sparsity of accessible atmospheric N_2O observations for the inversion models [9]. The sectorial analysis shows that cropland N_2O emissions from nitrogen fertilizer application are the single largest N_2O source at 0.8 ± 0.3 Tg N_2O yr^{-1} (Fig. 1 and Supplementary Table S2).

In summary, we have presented the first comprehensive GHG budget for terrestrial ecosystems in China. The integration of both bottom-up and top-down approaches, together with lateral adjustments, allows us to more confidently generate best estimates of the GHG budget (e.g. [10]). Although the existing wide array of accounting methods has made possible a comprehensive picture of the diverse contribution of terrestrial ecosystems to the GHG budget, each method offers its own benefits, as well as challenges and uncertainties. For example, although satellite GHG measurements have grown quickly in recent years, current atmospheric inversions still lack sufficient information from atmospheric observations over China, leading to the high sensitivity of posterior estimates to prior information (e.g. [11]). Such persistent challenges call for efforts to speed up the establishment of a measurable, reportable and verifiable system for GHG accounting.

Our results also imply the crucial importance and careful consideration needed for curbing GHG emissions. Because agricultural CH_4 and N_2O emissions offset >90% of the land CO_2 sink, curbing agricultural GHG emissions will probably attract increasing attention in the agenda to mitigate climate change. A successful mitigation strategy will have to rely on sufficiently scrutinized solutions, which should address GHG emissions reduction without endangering the food supply for China's >1 billion people and provide co-benefits for the environment (e.g. [12]). This represents a huge sustainability challenge that urgently requires further studies.

SUPPLEMENTARY DATA

Supplementary data are available at *NSR* online.

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Xuhui Wang [1,*], Yuanyi Gao [1], Kai Wang [1], Yuxing Sang [1], Yilong Wang [2], Yuzhong Zhang [3,4], Songbai Hong [1], Yao Zhang [1] and Wenping Yuan [5]

[1]Institute of Carbon Neutrality, Sino-French Institute for Earth System Science, College of Urban and Environmental Sciences, Peking University, China; [2]State Key Laboratory of Tibetan Plateau Earth System, Resources and Environment (TPESRE), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, China; [3]Key Laboratory of Coastal Environment and Resources of Zhejiang Province, School of Engineering, Westlake University, China; [4]Institute of Advanced Technology, Westlake Institute for Advanced Study, China and [5]School of Atmospheric Sciences, Sun Yat-sen University, China

[*]**Corresponding author.**
E-mail: xuhui.wang@pku.edu.cn

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