Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Regional trajectories of carbon stock and carbon pools in China's Harvested Wood Products

Nicklas Forsell

forsell@kaist.ac.kr

Korea Advanced Institute of Science and Technology

Minpeng Chen

Renmin University of China

Jinfeng Chang

Zhejiang University

Hongtak Lee

Korea Advanced Institute of Science and Technology

Hao Zhao

Hohai University

Ershi Hua

Renmin University of China

Hyungjun Kim

Korea Advanced Institute of Science and Technology

Research Article

Keywords: Harvested wood products, carbon storage, carbon accounting, climate mitigation, greenhouse gas balance, China

Posted Date: November 19th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11416238/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Harvested wood products (HWP) can reduce climate change by retaining biogenic carbon in products and substituting materials and energy carriers associated with higher emissions. China currently hosts around one third of the global HWP carbon sink, measuring at -110 $MtCO_2$ yr^{-1}, yet recent studies suggest that the sink is saturated, raising critical questions about its long-term sequestration potential. Previous forward-looking assessment have only assessed the development of the HWP carbon flux at the national scale, leaving unresolved how this transition is distributed among provinces and how accounting choices affects the regional attribution of carbon.

Here we show that China's HWP sink declines across all scenarios and accounting approaches, reflecting structural saturation driven by slowing growth in HWP production and consumption. By 2060, the national HWP sink is projected to decline by 30.5% to 91.5% from current levels, while its spatial distribution varies strongly with the selected accounting framework. Consumption-based accounting increases the national HWP carbon stock but does not fundamentally alter the long-term decline of the sink. Production-based accounting concentrates HWP carbon stocks in a few industrial processing provinces, whereas consumption-based accounting reallocates carbon towards highly populated regions, highlighting a mismatch between the physical carbon flows and accounting-based attribution. Stronger bioenergy demand may further accelerate the sink decline, while increased material use delays, but does not prevent, saturation. These findings reveal a fundamental distinction between the national HWP dynamics and provincial attribution of HWP fluxes. National assessment along may obscure substantial differences in where carbon storage occurs and where mitigation responsibilities are assigned.

1. Introduction

Land-based mitigation is an integral component of pathways compatible with the Paris Agreement, because the sector can contribute both by reducing greenhouse gas (GHG) emissions and by maintaining or increasing terrestrial carbon removals (IPCC, 2019a). Reducing emissions from land use while enhancing and conserving terrestrial carbon sinks is a central component of most Paris-aligned emissions scenarios (Rockström, 2017; IPCC, 2022; Harper, 2018; Rogelj, 2018; Roe et al. 2019). The vast majority of pathways that remain well below 2°C rely on rapid reductions in deforestation and increasing carbon removals from land sector (Lamb, 2024; Bustamante, 2023; Zhao, 2024; Smith, 2024). This importance is also reflected in national climate policies. The national determined contributions (NDCs) of more than 100 countries representing approximately 90% of the global forest area include forest-related actions (Fyson et al., 2019), while land use, land use change and forestry (LULUCF) accounted for roughly one-quarter of the mitigation pledged in the first round of NDCs (Forsell et al., 2016; Grassi et al., 2017). These commitments are also represented in the updated 2030 and 2035 NDC submissions (UNFCCC, 2025; den Elzen et al. 2022; Lou et al. 2024). The majority of assessment continues to identify substantial mitigation potential from the land sector, particularly over the period to 2030 and 2035 (IPCC, 2019b; Roe et al. 2019; Griscom, 2017; Chazdon, 2016; Austin et al. 2025).

China has similarly positioned the land and forest sector as an important component of its long-term climate strategy. Its Long-Term Low Greenhouse Gas Emission Development Strategy (LTS) targets carbon neutrality before 2060, following an earlier peak in carbon dioxide (CO_2) emissions before 2030 (Government of China, 2021). These ambitions were further specified in the 2035 NDC, which commits China to reducing economy-wide net GHG emissions by 7–10% relative to peak levels (Government of China, 2025). The NDC also establishes targets of more than 30% non-fossil energy in total consumption, at least 3.6 TW of installed wind and solar capacity, and forest stock volumes exceeding 24 billion m³.

Forest industries can influence the climate system through several complementary mitigation pathways. Carbon absorbed during forest growth can remain stored after harvest when biomass is converted into wood products, with the duration of storage depending on the product lifetime (Geng et al., 2017; Skog et al., 1998; Green et al., 2006; Head et al., 2019; Ludvig et al., 2021; Sato and Nojiri, 2019). Harvested wood products (HWP) can therefore temporarily retain biogenic carbon while also providing opportunities to displace carbon-intensive construction materials, including steel and concrete, steel and other construction products (Geng et al., 2017; Petersen, 2005; Sathre et al., 2010; Werner et al., 2005; Bergman et al., 2014). Woody biomass may additionally replace fossil energy sources in some applications (Favero et al., 2023), while engineered products such as glue-laminated and cross-laminated timber offer additional opportunities for material substitution in construction (Churkina et al., 2020; Pauliuk et al., 2021). These mitigation pathways nevertheless compete for a finite biomass resource. Large-scale expansion of bioenergy or material demand can alter forest-product markets, harvesting pressures and biomass allocation (Favero et al., 2017; Lauri et al., 2021), while increased plantation development and harvesting may also affect natural ecosystems and biodiversity (Burivalova, 2014; Chaudhary et al., 2016; Martin et al., 2015). Global assessments suggest that greater cascading and circular use of wood can help accommodate increasing demand for engineered products (Yayla et al., 2025), however, how these competing uses affect HWP carbon storage within individual countries and provinces remains insufficiently understood.

Carbon retained in semi-finished wood products has consequently become a quantitatively important component of the forest-sector carbon balance and here China provides a particularly important case. The global HWP sink was estimated at approximately − 335 $MtCO_2\ yr^{-1}$ in 2015, but this sequestration is highly concentrated geographically (Johnston et al. 2019). China currently accounts for − 110 $MtCO_2\ yr^{-1}$, compared to -91 $MtCO_2\ yr^{-1}$ in the United States, and approximately − 34 $MtCO_2\ yr^{-1}$ for EU27 (Government of China, 2024; EPA, 2024; EEA, 2025). China's large HWP sink is closely linked to the rapid expansion of its forest-processing industries. The sector grew from a comparatively small industrial base in the late 1970s into one of the dominant components of the national forest economy, with the value of forest-sector output increasing from 42.9 billion CNY in 1978 to approximately 7 trillion CNY in 2017 at constant 2017 prices (Ke et al., 2021). In 2023, China accounted for 43.9% of global wood-based panel production and 34.3% of global paper and paperboard production (FAO, 2025). These characteristics make China particularly relevant for assessing how changing production, consumption

and trade affect HWP carbon fluxes and how that flux is attributed under alternative accounting approaches.

Most earlier assessments of HWP carbon dynamics in China have focused on reconstructing historical stocks and fluxes at the national scale (Ji et al., 2016; Yang et al., 2016; Zhang et al., 2018, 2019, 2020). Although these studies differ in methodological assumptions and underlying datasets, they consistently show that the rapid expansion of China's wood-processing sector since 1990 has substantially increased the HWP carbon stock and that that HWP currently represents a notable carbon sink. This general pattern is also reflected in China's most recent national GHG inventory (NGHGI's) submitted as part of China's First Biennial Transparency Report (BTR) (Government of China, 2024). A smaller body of literature has examined the spatial distribution of HWP carbon within China and identified pronounced differences among provinces (Lun et al., 2012; Zhang et al., 2023). For example, Zhang et al. (2023) estimated that Guangxi, Heilongjiang and Fujian together accounted for 38.3% of the national HWP carbon stock. However, these provincial estimates allocate HWP carbon according to the geographic origin of harvested biomass rather than the location where semi-finished wood products are manufactured. Consequently, inter-provincial transfers of roundwood and the spatial separation between timber supply and wood processing are not considered.

Recent studies have begun to address the future development of China's HWP carbon pool, but important spatial and methodological gaps remain. Yu et al. (2022b) projected a substantial increase in the national HWP carbon stock, from 815.94 MtC to 3,254.37 MtC by 2050 under a business-as-usual pathway, although their projections did not explicitly incorporate several major land-use and forestry policies subsequently represented in more policy-constrained modelling frameworks. Forsell et al. (2024) addressed this limitation by coupling HWP carbon stock and flux estimates with GLOBIOM-China and showed that the annual national HWP sink is likely to weaken as the rapid expansion of wood-product production slows. Under a high-bioenergy pathway, annual sequestration was projected to fall to approximately – 33 $MtCO_2$ yr^{-1} by 2060. The declining sink strength is also consistent with China's NGHGI, which indicate that HWP sink has weakened since their 2015 peak (Government of China, 2018, 2023, 2024). These national level-assessment establish an emerging national saturation of China's HWP sink, but they do not reveal how this transition is distributed among provinces, whether saturation occurs uniformly across regions, or which provinces drive the changing national balance. Consequently, a national pathway can conceal substantially different provincial patterns of HWP carbon fluxes and mitigation potentials.

This spatial question is closely linked to the accounting approach being applied (Franzen et al., 2018). IPCC guidance allows HWP carbon to be attributed and reported using three alternative accounting frameworks: the Production Approach (PA), Stock-Change Approach (SCA), and Atmospheric-Flow Approach (AFA) (IPCC, 2003. 2006, 2013, 2019b). China's NGHGI currently reports HWP fluxes following the PA as specified in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), while previous studies have shown that alternative guidelines and consumption-based SCA accounting can increase the HWP carbon stock attributed to China (Yu et al., 2022a; Zhang et al., 2019). At the

provincial level, the distinction may be even more consequential as forest resources, wood-processing industries and final consumption are geographically separated. Production- and consumption-based accounting can therefore attribute the carbon associated with the same forest-product system to fundamentally different provinces. This raises a question that national HWP accounting cannot resolve; whether the geographical distribution of mitigation reflect where biomass originates, where HWP is manufactures, or where those products are finally consumed.

Previous assessments have assessed the implications of applying the PA formulations contained in the 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol (PA2013) (IPCC, 2013) and the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (PA2019) (IPCC, 2019b). Comparisons of these formulations show that the methodological revisions introduced between PA2013 and PA2019 can lead to higher estimates of China's HWP carbon stock (Yu et al., 2022a). Furthermore, because China is a major importer of biomass and wood products, applying the consumption-based SCA instead of the production-based PA has been argued to increase the carbon stock attributed to China by including imported products (Zhang et al., 2019). Since China's current timber supply gap is at least 200 million cubic meters (Mm^3) and is expected to continue to grow in the near future (Ke et al., 2021), it is therefore important to quantify how alternative HWP accounting approaches affect both national and provincial carbon stocks and fluxes.

Taken together, three gaps limit current understanding of China's future HWP mitigation potential. Existing forward-looking assessment have not: (1) resolved how projected national HWP sink saturation is distributed across provinces; (2) determined how competing future demand for woody biomass, particularly bioenergy and material use, alter these provincial trajectories; or (3) quantified how production- and consumption-based accounting influences the geographical attribution of HWP fluxes. These gaps matter because national estimates along cannot identify which provinces drive future change in the HWP sink or how mitigation responsibility shifts under alternative accounting conventions.

Here we address these knowledge gaps by extending the GLOBIOM-China and HWP-China frameworks to quantify HWP carbon stocks and fluxes across China's provinces to 2060 under business-as-usual, high-bioenergy, and high-material-use scenarios, while systematically comparing production-based (PA) and consumption-based (SCA) HWP accounting approaches. We ask three questions: (1) how is the projected national saturation of China's HWP sink distributed across provinces; (2) how do alternative future used of woody biomass reshape these regional trajectories; and (3) to what extent does the geographical attribution of HWP fluxes depend on whether carbon is accounted according to production of consumption? By jointly resolving temporal, spatial and accounting dimensions, the study distinguishes changes in the underlying development of China's HWP carbon pool from changes in where the carbon is attributed.

2. Methods and materials

This study combines wood product flow projections with IPCC-consistent carbon stock accounting to estimate province-specific trajectories of HWP carbon stocks and fluxes in China from 1961 to 2060. Within this framework, two accounting methods are adopted for estimating carbon fluxes from HWPs: PA, to ensure full consistency with China's national greenhouse gas inventories as reported in the First Biennial Transparency Report (Government of China, 2024), and SCA, following the methodological guidance provided in the 2006 IPCC Guidelines (IPCC, 2006). The framework is designed to capture both the policy relevance of nationally aligned reporting and the analytical value of an alternative accounting perspective. It also enables the estimation of HWP carbon dynamics at the provincial level by linking national-scale projections with subnational production and consumption distributions.

The analysis builds on the existing GLOBIOM-China and HWP-China modelling frameworks (Zhao et al., 2021; Forsell et al., 2024), which are extended here to support provincial-scale analysis and comparison of PA and SCA accounting. GLOBIOM-China is a spatially explicit partial equilibrium model that simulates the production, consumption, and trade of forest products under different policy and market conditions (Havlík et al., 2011; Zhao et al., 2021). It provides scenario-based trajectories of national production, consumption, and international trade in semi-finished wood products and woody biomass. These outputs serve as inputs to the HWP-China model, which estimates annual carbon inflows and outflows and tracks the accumulation and decay of carbon stored in wood products over time based on either production flows or consumption flows and product-specific lifetimes. To improve its suitability for this study, three refinements are introduced to the HWP-China model. First, the model is adapted to calculate HWP carbon pool dynamics under both the PA and SCA methods. Second, it is refined to estimate provincial production and/or consumption of each semi-finished HWP category. Provincial production is derived by allocating national GLOBIOM-China estimates using provincial production statistics from the China Forestry Statistical Yearbooks (SFA, 2024). Provincial consumption is estimated by distributing national consumption totals across provinces using population density maps (Ciais et al., 2026).

2.1. The GLOBIOM-China model

GLOBIOM-China represents interactions among agricultural, forestry and bioenergy markets within a spatially resolved partial-equilibrium framework (Havlík et al., 2011, 2014; Zhao et al., 2021). The model is a China-specific configuration that incorporates country-specific representations of land use, agricultural production, environmental constraints and land-use policies. The forestry module used in this study follows the configuration documented by Forsell et al. (2024), in which woody biomass flows are represented from primary feedstocks and processing residues through intermediate and final forest products. The model therefore captures production and market interactions across major commodities including industrial roundwood, sawnwood, wood-based panels, pulp, fuelwood, pellets and other energy-wood products. Forest-industry production capacity evolves endogenously after 2020 in response to expected revenues and annualized investment costs, while conversion processes are represented through fixed input–output relationships with defined substitution possibilities among biomass inputs. These features allow GLOBIOM-China to project internally consistent changes in wood production, consumption and trade under the alternative policy and demand scenarios considered in this study.

The spatial representation of forests in GLOBIOM-China follows the calibration described by Forsell et al. (2024). Forest distribution is represented at 0.5° resolution using the GLC-2015 land-cover dataset (Li et al., 2023) together with forest-management information from Lesiv et al. (2022). Gridded forest areas were reconciled with the Global Forest Resources Assessment 2020 (FAO, 2020), while the China-specific calibration uses provincial information from the Ninth National Forest Inventory (Government of China, 2019). This calibration yields approximately 220 Million hectares (Mha) of forest in 2020, comprising about 140 Mha of natural forest and 80 Mha of planted forest.

2.2. HWP accounting approaches: Production vs. Consumption

HWP carbon fluxes are estimated and reported following internationally recognized methodological approaches defined by the IPCC (IPCC 2003; IPCC 2006; IPCC 2013; IPCC 2019b). In this study, HWP carbon fluxes from are estimated following the PA and the SCA accounting approaches defined by the IPCC (IPCC, 2006).

Under the PA approach, carbon fluxes are attributed to the country or region where HWP commodities (i.e., sawnwood, wood-based panels, and paper and paperboard) are produced using domestically harvested biomass. Under PA, the reported HWP pool is restricted to products derived from domestically harvested wood, with subsequent carbon releases attributed to the same reporting entity. Consequently, traded products do not transfer HWP carbon stocks between reporting boundaries under this approach. Accordingly, only products derived from domestic feedstocks contribute to the carbon stock. In contrast, under the SCA approach, carbon fluxes are attributed to the location of final consumption, irrespective of the origin of the raw material. Accordingly, SCA requires that a country report on all HWP consumed, as well as the carbon released by their decay or oxidative decomposition. As a result, imported wood products contribute to the domestic HWP carbon pool under the SCA approach, while exported products are excluded.

The key distinction between the two approaches therefore lies in the underlying activity data being used and system boundary of the HWP carbon pool. This difference directly affects both the magnitude and the spatial distribution of carbon stocks and fluxes, and in this study, both the PA and SCA approaches are implemented within the HWP-China modelling framework, allowing for a consistent comparison of how accounting choices influence national and provincial HWP carbon dynamics.

2.3. Data sources

This study integrates multiple datasets to represent national and provincial dynamics of harvested wood products. Historical production, consumption, and international trade of biomass resources and semi-finished HWP commodities is derived from FAOSTAT (FAO, 2025). These data form the basis for model calibration and are used consistently for the PA and SCA approaches.

Provincial-level production data are derived from the China Forestry Statistical Yearbooks (SFA, 2024), which provide information on the output of key wood product categories for the period 1999–2022 for

each province (excluding Hong Kong, Macau, and Taiwan). Due to the absence of direct data on paper and paperboard production at the provincial level, roundwood consumption for paper production is used as a proxy, following established approaches in the literature (Zhang et al., 2023). The proxy data are available for the period of 2000 to 2016 (SFA, 2024).

Information on provincial consumption of HWP commodities is not directly available. Therefore, national consumption is distributed across provinces using population density as a proxy for regional demand (Ciais et al., 2026). Spatially explicit population datasets (Hua et al. 2025) are used to provide consistent historical and projected population distributions from 1990 to 2060.

Data gaps in provincial statistics are addressed using interpolation and averaging methods. For years prior to the availability of provincial production data, values are approximated using the average of the earliest available observations. Thus, the provincial production estimates are set as the average for the first five years of data (i.e. 1999 to 2003 in the case of sawnwood, plywood, fiberboard, and wood panels; and 2000 to 2004 for roundwood for paper production).

Differences in temporal coverage between datasets are as such accounted for to ensure consistency in the construction of provincial time series.

2.4. Model calibration and harmonization

To ensure consistency with international reporting standards and China's national greenhouse gas inventories, the HWP-China model is calibrated following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), which are currently applied in China's NGHGI (Government of China, 2024).

First, model parameters governing the decay of harvested wood products are aligned with IPCC default values. In particular, the service lives of HWP commodities (i.e., sawnwood, wood-based panels, and paper and paperboard) are set according to the 2006 IPCC Guidelines (IPCC, 2006). While China's BTR indicates the use of country-specific parameters derived from surveys and expert judgement as well as adjusted based on economic development and changes in consumption habits, these values are not publicly available (Government of China, 2024). Therefore, the use of IPCC default values provides the closest reproducible approximation of the methodology applied in the NGHGI. The same parameterization is used for both the PA and SCA implementations to ensure methodological consistency with IPCC Guidelines (IPCC, 2006).

Second, the model is calibrated against national FAOSTAT activity data for 1961–2023, covering production, consumption, and trade in the relevant wood product categories (FAO, 2025).

Third, to ensure consistency between model outputs and observed statistics, discrepancies between GLOBIOM-China estimates and FAOSTAT data are reconciled through a harmonization procedure. Specifically, a constant offset value, defined as the difference between model estimates and reported statistics in the harmonization year (2023), is applied to align production, consumption, and trade flows

(Rogelj et al. 2011). This offset is assumed to remain constant over the projection period (2023–2060), thereby ensuring a consistent evolution of the HWP carbon pool over time.

Through this multi-step calibration, the HWP-China model reproduces historical HWP carbon fluxes in close agreement with China's NGHGI estimates, providing a robust basis for scenario analysis and provincial-level assessments.

2.5. Provincial allocation and methodology

To estimate HWP carbon stocks and fluxes at the provincial level, national activity data are distributed across provinces based on production and consumption patterns.

For the production-based approach, national production of wood products is allocated to provinces using production shares derived from the China Forestry Statistical Yearbooks (SFA, 2024). These shares are calculated for each HWP commodity and year and applied to national totals. This ensures consistency with national statistics while capturing spatial heterogeneity in industrial activity.

For the consumption-based approach, national consumption is distributed across provinces using population density as a proxy for demand. This approach assumes that wood product consumption is correlated with population distribution, which is supported by previous studies (Ciais et al., 2026).

For the projection period, provincial production shares are assumed to remain constant based on the average over the last ten years of available historical data (i.e. 2013 to 2022 in the case of sawnwood, plywood, fiberboard, and wood panels; and 2007 to 2016 for roundwood for paper production). This assumption reflects the absence of detailed projections of sub-national industrial relocation and consumption patterns. Population projections are used to estimate future consumption patterns. This approach enables consistent estimation of provincial carbon dynamics under both accounting approaches while preserving consistency with national totals.

2.6. Scenarios

As part of this assessment, three scenarios with different assumptions relating to the national demand of wood for bioenergy and materials are used to analyze their impacts on China's HWP carbon pool development and the extent to which China's provinces can help the country to meet its international climate commitments. The scenarios are based on a recent study (Zhao et al., 2021) and explores the long-term tradeoffs between climate policy developments incentivizing bioenergy and increased carbon sequestration in wood products. As such, the scenarios highlight potential tradeoffs between bioenergy and wood product use. The three scenarios are defined as follows.

The business-as-usual (BAU) scenario represents the development of China's forest sector under the SSP2 "middle-of-the-road" Shared-Socioeconomic pathway (Fricko et al., 2017). Recent patterns in consumption and technological change are broadly maintained, while the China-specific implementation incorporates major forestry, agricultural and environmental policies (Zhao et al., 2021). To enhance the representation of China, the scenario also mimics important policies in the forestry, agricultural, and

environmental sectors. The 1990s afforestation policy has been one of the most significant historical drivers of land use in China (Chen et al. 2019). A total of 53 Mha has already been afforested at the expense of cropland, pastures and other lands (unmanaged grassland and shrubland, non-/ sparse vegetation). The GLOBIOM-China is calibrated to the 2000–2020 period forest area change based on statistical data, and the scenario assumes that the National Forest Management Plan (2016–2035) afforestation goal is achieved. Future forest expansion is also constraint in accordance with existing policies and plans. Total forest area is set to reach 230.5 Mha by 2025 in accordance with the 14th Five-Year Plan, and to reach 249.6 Mha by 2035 in accordance with the National Major Project for the Protection and Restoration of Important Ecosystems. With regards to forests managed for timber production, the scenario accounts for the establishment of an additional 13 Mha between 2020 and 2035 in accordance with the National Reserve Forests Construction Plan.

The high-bioenergy (HB) scenario represents a stringent mitigation pathway compatible with a 1.5°C global warming limit (Rogelj et al., 2018). By 2060, a substantial increase in primary biomass consumption for energy will be required, from 57 EJ in 2020 to 152 EJ (Zhao et al., 2021). A part of this project is expected to be combined with carbon capture and storage (CCS) technology in order to produce negative emissions (i.e., BECCS) and a carbon price of 568 USD per ton of CO2, as projected by the integrated assessment model MESSAGE-GLOBIOM.

Under this scenario, China would be able to achieve its LTS target of becoming carbon neutral before 2060 with BE at 14.1 EJ (representing 9.3% of global BE demand).

The high-material-use (HM) scenario explores the implications of stronger domestic demand elasticity for wood-based materials in China. Demand for HWP commodities follows the higher-consumption trajectory associated with SSP5 (Kriegler et al., 2017), resulting in greater demand of semi-finished wood commodities than under BAU, with the strongest increases occurring for wood-based panels and paper and paperboard. Other commodity demands, including food and non-wood fibres, retain the BAU assumptions so that the scenario isolates the effect of stronger material demand within the forest sector. The HM scenario therefore provides a counterpoint to the HB pathway by examining whether greater material use can sustain HWP inflows and delay the decline of the HWP carbon sink.

3. Results

3.1. Trajectories of the national HWP flux

From 1990 to 2023, HWP acted as a net carbon sink in China, sequestering more carbon than it was emitting (Fig. 1a-b). Historical sequestration rates are higher following the PA approach than the SCA approach, as HWP consumption has generally exceeded production based on domestically sourced feedstocks, particularly for long-lived products such as wood-based panels and sawnwood.

The national HWP sink increased steadily between 2000 and 2010, followed by a period of stabilization and gradual decline. The national net HWP sequestration rate peaked in 2013 at -135.9 $MtCO_2\ yr^{-1}$ following the PA approach, and in 2017 at -205.9 $MtCO_2\ yr^{-1}$ following the SCA approach. This change coincides with slower growth in China's production and consumption of semi-finished HWP commodities, most notably wood-based panels. Under PA, the growing contribution of imported feedstock further weakens the amount of carbon credited to the domestic HWP pool. Among the individual HWP categories, wood-based panels have historically made the largest contribution to net sequestration, independent of the accounting approach being used. For the PA approach, this finding is consistent with the substantial increase in the domestic production of plywood for this period (SFA, 2024). Sawnwood is also a contributor to the HWP sequestration rate, but at a lower rate than wood-based panels, as the national sawnwood production and consumption levels are lower than wood-based panels (SFA, 2024). While paper and paperboard products have contributed to the HWP sequestration rate for most years, their contribution to the total sink is minor for both accounting approaches.

Our estimates of the national HWP net carbon sequestration rate following the PA approach (Fig. 1a) exhibit consistent temporal patterns with China's NGHGI's submitted to the UNFCCC (Government of China, 2018; Government of China, 2023; Government of China, 2024). There is an average difference of less than 4.2% between the HWP-China estimate and the NGHGI estimates. These consistencies in estimates demonstrates that the methodological choices and input data on activates and half-lives for the HWP-China model closely correspond to those used for assessing China's NGHGI. These results offer an important context for understanding the ability of China's provinces to mitigate climate change by storing carbon in wood products, as well as the extent to which China's provinces can help the country meet its international climate commitments.

Under the BAU scenario, China's HWP sink weakens progressively toward 2060 independent of the HWP accounting approach being applied (Fig. 1). The decline reflects a transition from the rapid expansion of wood-product production and consumption observed during the 2000s toward slower growth rates in subsequent decades. For example, domestic production of wood-based panels increased by 36% between 2010 and 2020 but is projected to grow by only 12.9% between 2020 and 2030. As the input to the HWP pool grows more slowly, it increasingly approaches the output from the HWP pool related to products reaching the end of their service lives, thereby reducing the annual net sequestration rate. The decline of the net HWP sequestration rate is stronger under the SCA approach because consumption growth slows more rapidly than domestic production growth. Between the historical peak and 2060, annual sequestration decreases by 41.5 $MtCO_2\ yr^{-1}$ following the PA approach and by 129.2 $MtCO_2\ yr^{-1}$ following the SCA approach. These results indicate that the weakening of the HWP sink under BAU is driven primarily by maturation of the HWP production and consumption sectors rather than by an absolute contraction of the HWP carbon stock.

The development of China's forest industries has also led to an increase of the domestic HWP carbon stock (Fig. 1c-d). As of 2023, China's total carbon stock of HWP reached 778 MtC following the PA approach, and 1098 MtC following the SCA approach. Although the national HWP sequestration rate is

expected to decline over time, it will remain a sink until 2060, as the HWP carbon stock is increasing over time. It is projected that by 2060, China's total carbon stock of HWP will reach 1873 MtC following the PA approach, and 2368 MtC following the SCA approach.

In the HB scenario, the reduction of the Chinese HWP sequestration rate over time is even more pronounced than that in the BAU scenario, independent of the HWP accounting approach being applied. This illustrates the tradeoffs between the use of biomass for bioenergy and for material in China. In the HB scenario and following the PA approach, the annual HWP sequestration will only be -11.6 $MtCO_2\ yr^{-1}$ by 2060, a reduction of the HWP sequestration rate by as much as 124.3 $MtCO_2\ yr^{-1}$ between the peak of the sink in 2013 and 2060. If the SCA approach is applied, the annual HWP sequestration will be -48.2 $MtCO_2\ yr^{-1}$ by 2060, a reduction of the HWP sequestration rate by 157.6 $MtCO_2\ yr^{-1}$ from the peak of the sink in 2017 to 2060. Following the PA approach, the reduction of the HWP sink is primarily due to the intensified competition for biomass resources caused by the expansion of the bioenergy industry. As a result, domestic production of sawnwood and wood-based panels in 2060 will decrease by 68% and 18%, respectively, from the BAU scenario. In addition, by 2060, China is expected to import 128 Mm^3 more roundwood than it would have in the baseline scenario. It is important to note that by relying heavily on imported roundwood for semi-finished wood products, the net carbon sequestration rate for HWP is further diminished, since the PA approach only accounts for HWP commodities produced domestically and using domestic biomass sources. Furthermore, imports will not be sufficient to offset the decline in national production of HWP, which will result in a decline in overall consumption. As a result, when applying the SCA approach to the HB scenario, the HWP sink becomes lower than it would be in the BAU scenario.

If steps are taken to promote the consumption of HWP products within the country, the peak of the HWP sink can be delayed and the decline in the HWP net carbon sequestration rate can be reduced, independent of the HWP accounting approach being used. Under both accounting approaches, net HWP sequestration strengthens until approximately 2030 before gradually weakening toward 2060. Relative to BAU, the additional material demand increases the HWP carbon stock by 8.2% under PA and 13.6% under SCA by 2060, reaching 2027 MtC and 2689 MtC, respectively. The effect on annual sequestration is more persistent under SCA because the accounting framework captures changes in national consumption irrespective of the origin of the underlying biomass. Under PA, by contrast, the advantage over BAU diminishes as domestic production of sawnwood and wood-based panels converges toward BAU levels during 2040–2050. Consequently, the HM pathway can delay the weakening of the HWP sink and increase cumulative carbon storage, but it does not prevent the longer-term decline in annual sequestration.

3.2. Trajectories of the provincial HWP fluxes

Between 1990 and 2000, the spatial variations between provinces in terms of net HWP sink and stock was small. Since then, the development of Chinese wood processing industry has resulting in large differences between the provinces in terms of the production of HWP commodities and the resulting

HWP flux (Fig. 2). However, the pattern across provinces varies significantly depending on HWP accounting approach being used as the consumption of HWP commodities remained relatively evenly distributed throughout the country (Supplementary Figs. 1, 2, 3, 4).

Following the PA approach, the current HWP carbon sink and stock is highly concentrated in three provinces across the east and south of China, namely Shandong, Jiangsu and Guangxi. In 2020, these three provinces' account for as much 47.8% of the total national HWP sink and 37.7% of the total national HWP carbon stock. Given that these are provinces that historically have been large producers of HWP commodities (SFA, 2024), it is natural that these provinces also represent a large portion of the national HWP sink and HWP carbon stock. As of 2020, these three provinces accounted for 49.6% of the national production of wood-based panels and 37.5% of the national production of sawnwood. However, the consumption of HWP commodities is showing very different spatiotemporal variations and trends than that of the production. Following the SCA approach, the HWP carbon stock and sink is much more evenly distributed across the provinces of China. The three provinces with the highest concentration of the HWP carbon sink are Guangdong, Shandong and Henan. Jointly, these three provinces' only account for 23.7% of the total national HWP sink and 22.3% of the total national HWP carbon stock.

The currently observed spatial variations of the HWP carbon sink and stocks are projected to remain relatively stable until 2060 in the BAU scenario. In the case of the PA approach, the provinces of Shandong, Jiangsu and Guangxi are projected to account for 47.4% of the total national HWP sink by 2060 (Fig. 3). However, their importance in terms of the national HWP carbon stock will increase to reach 44.7% as these provinces have high HWP sinks and continue to accumulate their carbon stocks over time. The SCA approach is expected to preserve the spatial variations of the HWP carbon sinks and stocks even more than PA approach. By 2060, the Guangdong, Shandong and Henan will account for 24.5% of the total national HWP sink and 22.9% of the total national HWP carbon stock.

3.3. Peak of HWP fluxes at the provincial scale

Spatiotemporal variation between the PA and SCA approaches can also be observed in terms of the HWP carbon stock peak year for the provinces (Fig. 4). When applying the SCA approach, no province will reach a peak in their HWP carbon stocks before 2060 under any of the scenarios (i.e., BAU, HB, HE). Across all provinces and all scenarios, the HWP carbon stocks have increased from 1990 to 2020 and are projected to further increase until 2060. This is the case as the HWP sink is relatively evenly spread across the provinces, and all provinces have higher HWP removals than HWP emissions, thereby remaining net sequesters rather than switching to becoming net emitters.

On the other hand, when using the PA approach, several provinces reach a peak in their HWP carbon stocks before 2020. This is the case for the western provinces of Xizang, Ningxia and municipalities such as Shanghai, Beijing, and Tianjin. The carbon stocks in these provinces are relatively small and they jointly only account for 1.0% of the total national HWP carbon stock by 2016. The production of semi-finished HWP has transitioned away from these provinces and municipalities over time as the demand

for processed woody products has increased and the forest products industry has developed (Ke et al. 2021).

From 2020 to 2060, no provinces are projected to reach a peak in their HWP carbon stocks for the BAU and HM scenarios, when using the PA approach. However, several provinces are projected to have a peak in their HWP carbon stocks between 2020 and 2060 for the HB scenario as the production of domestic HWP commodities decreases and the HWP flux switches from being a sink to becoming a source of emissions. In this scenario, ten provinces are projected to have a peak in terms of their HWP carbon stocks between 2030 and 2050. This includes the provinces of Neimenggu, Liaoning, Heilongjiang, Zhejiang, Hunan, Hainan, Guizhou, Yunnan, Gansu and Xingjiang. While these provinces do see a peak in terms of their HWP stock before 2060, their HWP stocks are not significantly depleted by 2060. By 2060, their combined HWP stocks have only been reduced by 0.01 MtC as compared to the province's peak levels, representing an average 4.6% reduction of their HWP stocks.

The peak year of HWP carbon sink for the provinces shows similarities in trends for the PA and SCA approaches. Also, the majority of provinces have already reached their peak year, independent of the HWP accounting approach being applied. Under the BAU and HB scenarios, all provinces have already reached the peak year by 2022 under the PA approach and by 2025 under the SCA approach. If steps are taken to promote the consumption of HWP products within the country, the peak in the HWP sink for the province of Jiangsu can be delayed until 2030 following the PA approach. Following the SCA approach, the increase in consumption of HWP commodities can delayed the peak year for a few provinces until 2030 (Jiangxi, Yunnan) and 2040 (Guangxi, Hainan, Guizhou and Xingjiang). However, it should at the same time be noted that the delay of the peak year for the HWP carbon sink does not lead to a strong reduction of the HWP sink.

4. Discussion

4.1. Implications of accounting approaches: Production vs. Consumption

This study demonstrates that the choice of accounting framework fundamentally alters how much HWP carbon is attributed to China and where that carbon is spatially assigned across its provinces. While previous studies have argued that the SCA approach is more favorable for China due to its role as a major importer of wood products (Zhang et al., 2019), our results show that the long-term trajectory of the HWP carbon sink is largely independent of the HWP accounting approach being used. In all scenarios considered, the HWP sink exhibits clear signs of saturation over time.

The key distinction between the PA and SCA approaches lies in the underlying activity data: PA attributes carbon to the location of production using domestically sourced biomass, whereas SCA attributes carbon to the location of final consumption regardless of origin. As a result, SCA yields a larger national HWP carbon stock and sink for China, reflecting the contribution of imported wood products. However,

this increase does not alter the long-term dynamics of the system, which are driven primarily by the slowing growth rates of HWP production and consumption. Chinese wood processing has seen a remarkable growth over the last thirty years, and although assessments indicate that the sector will continue to growth (Yu et al. 2022b; Forsell et al. 2024), the previous high growth rates are not expected to continue.

At the provincial level, the choice of HWP accounting approach has strong implications. Under PA, HWP carbon stocks and fluxes are highly concentrated in a limited number of wood processing provinces, such as Shandong, Jiangsu, and Guangxi. Jointly, these three provinces are accessed to account for 43.8% China’s national HWP carbon stock as of 2020. These provinces are not necessarily major sources of forest biomass but instead act as processing hubs for wood products, often relying on feedstock sourced from other provinces or international markets. This concentration of HWP carbon in a small number of processing regions contrasts with earlier provincial assessments (Lun et al., 2012; Zhang et al., 2023), which attribute HWP carbon to the location of timber harvest rather than product manufacturing. Following the PA approach, Zhang et al. (2023), for example, attributed 38.3% of China's national HWP carbon stock to Guangxi, Heilongjiang and Fujian. The difference illustrates the importance of explicitly representing movements of timber and processed wood commodities between provinces. Our results therefore indicate that domestic supply chains redistribute a substantial amount of embodied HWP carbon between provinces.

The geographical distribution of China's HWP carbon pool also differs markedly from the distribution of its forest resources. This is of particular significance when it comes to China's 123.7 million hectares of natural forest vegetation, these forests are subject to stringent national management and conservation policies (Government of China, 2019). The Ninth National Forest Resources Inventory (2014–2018) identifies Xizang, Yunnan, Sichuan, Heilongjiang and Inner Mongolia as the five provinces with the largest forest stock volumes (Government of China, 2019). These five provinces account for 59% of China's natural forest area. In spite of this, these provinces account for only 9.8% of the national HWP carbon stock as of 2020 and are expected to account for 8.8% of the national HWP carbon stock by 2060. In contrast, provinces such as Guangxi have large forest plantations that industries can utilize for feedstock. This shows how China’s wood processing industry has transitioned from logging primarily from natural forests to largely from plantations and agroforests (Ke et al. 2021).

4.2. Saturation of China’s HWP carbon sink

There are many ways in which our result contributes to the existing literature on HWP carbon flows in China. The assessment confirms and extends previous findings that China’s HWP carbon sink is approaching saturation (Forsell et al. 2025). This saturation is observed across all scenarios and reflects a fundamental shift in the dynamics of the HWP carbon pool. Furthermore, the saturation is particularly evident in scenarios with high estimates for bio-

A reduction of the HWP carbon sink does not necessarily mean that China's wood processing industry or forests are in decline, but rather that the inflow to the pool (newly produced or consumed wood products

entering use) is approaching a dynamic equilibrium with the outflow

(products reaching the end of their service life and releasing carbon). During periods of rapid industrial expansion, such as China's wood processing boom between 2000 and 2010, inflows significantly exceeded outflows, resulting in a strong and growing carbon sink. However, as growth in production and consumption slows, inflows stabilize while outflows continue to increase due to the accumulation of products in use. This leads to a gradual convergence toward equilibrium, where inflows and outflows become balanced and the net sink diminishes. Importantly, a declining HWP carbon sink does not imply a weakening of the forest sector or reduced climate benefits of wood use. Rather, it reflects a maturation of the system. The total HWP carbon stock continues to increase over time, even as the annual sequestration rate declines. However, the reduced sink strength limits the potential of HWP to offset residual emissions in the future, which is particularly relevant for achieving long-term climate neutrality targets.

The saturation effect is further amplified under the high-bioenergy (HB) scenario. In this case, systemic changes in the forest sector—driven by increased demand for bioenergy, higher carbon prices, and shifts in land use and market dynamics—reduce the inflow of long-lived wood products into the HWP pool. This results in a more pronounced decline in the HWP carbon sink. Conversely, the high-material use (HM) scenario delays the onset of saturation by increasing demand for wood products, thereby sustaining higher inflows in the short to medium term. Nevertheless, even under this scenario, saturation is not avoided but only postponed.

Other measures can also be taken to enhance the inflow and the composition of the HWP pool, such as increasing the consumption of engineered wood for construction (Churkina et al. 2020; Pauliuk et al. 2021), increasing the utilization rate of recovered paper (Yu et al. 2022b), and increasing the proportion of sawnwood and wood-based panels used for long-lasting products such as structural materials in construction (Yu et al. 2022b). While such adjustments and optimizations to the wood utilization structure can improve the HWP carbon pool, it is important to keep in mind the timing of such effects. For example, most of the carbon emission benefits of increasing the production or consumption of long-lived woody products such as engineered wood as construction material will only come into play after mid-century (Mishra et al. 2022). Finally, even though these alternatives have long-term climate benefits, it is important to note that the size of the HWP carbon pool is estimated and reported based on the production or consumption of semi-finished wood products (i.e. sawnwood, wood-based panels, paper and paperboard), not on the production or consumption of finished wood products (furniture, windows, wall paneling, wall systems, transmission poles, book, newspaper) (IPCC 2003; IPCC 2006; IPCC 2013; IPCC 2019b). As such, it is important that policies aiming to increase the HWP carbon pool targets the production or consumption of semi-finished products to ensure that measurable improvements to the HWP sink can be achieved. However, these findings highlight an inherent limitation of relying on HWP as a long-term mitigation strategy: while increasing production or consumption can temporarily enhance the carbon sink, structural dynamics ultimately constrain its long-term growth.

4.3. Uneven spatiotemporal development and policy implications

The analysis reveals a pronounced and persistent spatial heterogeneity in HWP carbon stocks and fluxes across China's provinces, particularly under the PA approach. A small number of provinces dominate the national HWP carbon sink due to their role as industrial processing centers, while forest-rich provinces contribute relatively little to the HWP carbon pool. In contrast, under SCA, carbon stocks are distributed more evenly across populous provinces. This suggests that large volumes of semi-finished wood products are transported from production hubs to consumption centers, redistributing carbon across the country. The divergence between PA and SCA results also highlights a structural mismatch between the physical flow of carbon in wood products and its accounting-based allocation across regions. While carbon embodied in HWP may originate in forest-rich provinces or abroad, it is attributed either to processing regions (PA) or consuming regions (SCA), depending on the accounting framework.

These findings have important implications for the design of sub-national climate policies, as different accounting approaches may assign mitigation responsibility to different regions. First, depending on the accounting framework, responsibility for HWP-related mitigation may be assigned to fundamentally different regions. Production-based accounting places the burden on industrial provinces, while consumption-based accounting shifts responsibility toward demand centers. Second, provinces with abundant forest resources are not necessarily those that benefit from HWP-related carbon sinks. This misalignment may lead to inefficiencies in policy design if forest management and industrial development strategies are not coordinated. Third, given the strong spatial heterogeneity, province-specific mitigation strategies are essential. Processing regions may focus on improving material efficiency and extending product lifetimes, while forest-rich regions may prioritize sustainable biomass supply and ecosystem conservation. It also emphasizes that national-level assessments may obscure important regional dynamics, and that incorporating sub-national perspectives is critical for effective climate policy design.

4.4. Limitations

This study highlights important aspects related to the spatiotemporal development of China's HWP carbon pool, although there remain uncertainties that should be acknowledged and there are several opportunities for improvement in future research. First, while international trade from FAO (FAO, 2025) is used to estimate the national share of HWP originating from domestic harvests and the total consumption of HWP semi-finished products, the port of entry and/or exit to China is now known and not accounted for. If province specific data on international trade were to be integrated to the assessment, a different picture could emerge. This is of particular importance when applying the PA approach which requires the calculation of a provincial share of HWP originating from domestic harvests. The approach used in this assessment introduces some level of uncertainty, and further investigation into international and provincial trade dynamics would provide more accurate estimates of HWP carbon fluxes.

In our study, we did not consider province-specific and time-dependent adaptations to the HWP half-lives. Future studies could incorporate dedicated scenarios to explore the potential impacts of changes to HWP service life calculated using country- or province-specific parameters obtained from surveys and adjusted based on economic development and changes in consumption habits as such data becomes available. In addition to building on previous studies conducted at the national level (Yu et al., 2022a), such assessments can demonstrate provincial differences in the potential for increasing the HWP carbon sink through the use of sawnwood and wood-based panels for long-lasting products (such as structural materials for construction). Additionally, we did not consider wood or energy product substitution effects that may occur when HWP commodities replace emission-intensive building materials (e.g. steel, concrete) or fossil fuel energy sources (e.g. coal, natural gas). This is due to a lack of available data or missing data at the provincial level, as well as the fact that such changes to GHG emissions would be accounted for in other sectors' GHG reporting.

5. Conclusions

Despite these limitations, our findings clarify how carbon stored in HWP, and its distribution among provinces, may contribute to China’s pathway towards climate neutrality before 2060. Over recent decades, China has strengthened its terrestrial carbon sink through extensive restoration and afforestation initiatives, notably the Three-North Shelter Forest Program, the Natural Forest Conservation Program, and the Grain-to-Green Program (Liu et al., 2014; Lu et al., 2018; Fang et al., 2001). Together, these initiatives have supported the expansion of China's LULUCF sink, while growth of the domestic wood-processing sector has created an additional reservoir of carbon in HWP (Government of China, 2024; Yu et al., 2022b). However, our results indicate that the HWP sink is likely to decline over time due to structural saturation driven by slowing growth in HWP production and consumption. The results further reveal a trade-off between allocating woody biomass to energy uses and retaining carbon through longer-lived material applications. As investment in nature-based mitigation expands, these competing uses of forest biomass reinforce the importance of coordinating policies across forest management, energy and material-use strategies so that mitigation benefits are considered across carbon pools and sectors. Building on the national assessment of Forsell et al. (2024), the present analysis identifies how HWP carbon storage is distributed among China's provinces and how this distribution varies with the accounting approach applied. Because the estimates are constructed consistently with the methodology underlying China's NGHGI, the resulting provincial trajectories provide a policy-relevant basis for considering HWP in future sub-national forest-sector mitigation strategies.

Additionally, the analysis highlights trade-offs between alternative forest sector pathways. Increased demand for bioenergy under stringent climate mitigation scenarios accelerates the decline of the HWP carbon sink, driven by systemic changes in market conditions, relative prices, and resource allocation within the forest sector. In contrast, increased material use of wood products can delay—but not prevent—the saturation of the HWP carbon sink by maintaining stronger additions to the product pool over the coming decades. Designing forest-sector mitigation strategies therefore requires balancing opportunities for more efficient material use against the wider market consequences of substantial

bioenergy expansion. While global assessments have captured net mitigation potentials across multiple dimensions (Daigneault et al., 2022; Fuller et al., 2025), future assessments should extend this analysis to outcomes such as employment, rural development, biodiversity and broader socioeconomic effects, as well as the costs and benefits of policy instruments targeting HWP carbon fluxes. Such analysis would allow environmental, economic and social consequences to be considered jointly when designing future policies for China's forestry and wood-processing sectors.

Provincial information on HWP carbon flows can support more geographically targeted forest and wood-industry policies. Improving this evidence base will require stronger sub-national carbon accounting and monitoring, together with better information on the movement of semi-finished wood commodities and their subsequent allocation to end uses. China's forestry and wood-processing sectors have undergone substantial transformation over the past four decades, alongside increases in forest area, growing stock and wood production. Further improvements in forest management and processing efficiency could influence both the future availability and use of wood products. Technological change may also broaden the range of forest-based products beyond conventional HWP categories, including emerging applications in biochemicals and fibre-based materials. Accounting for these developments will be important for ensuring that future forest-sector strategies jointly consider carbon storage, sustainable resource use and wider socioeconomic objectives.

Declarations

Author Contribution

N.F., M.C., J.F and H.Z. designed the study. H.L., E.H., and H.K. contributed the data analysis. N.F., M.C. and J.F wrote the manuscript with contributions from H.L., E.H., H.Z. and H.K. Preparation of figures for the paper was done by H.L., E.H. and N.F. All authors contributed to the interpretation of the results and commented on the manuscript.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. Austin KG, Favero A, Forsell N, Sohngen BL, Wade CM, Ohrel SB, Ragnauth S (2025) Targeting climate finance for global forests. Nat Commun 16(1):6443. https://doi.org/10.1038/s41467-025-61657-6
2. Bergman R, Puettmann M, Taylor A, Skog KE (2014) The carbon impacts of wood products. For Prod J 64(7–8):220–231. https://doi.org/10.13073/FPJ-D-14-00047

3. Buongiorno J, Johnston C, Zhu S (2017) An assessment of gains and losses from international trade in the forest sector. Policy Econ 80:209–217. https://doi.org/10.1016/j.forpol.2017.04.004
4. Burivalova Z, Şekercioğlu ÇH, Koh LP (2014) Thresholds of logging intensity to maintain tropical forest biodiversity. Curr Biol 24(16):1893–1898. http://dx.doi.org/10.1016/j.cub.2014.06.065
5. Bustamante M, Roy J, Ospina D, Achakulwisut P, Aggarwal A, Bastos A, Zscheischler J (2023) Ten new insights in climate science 2023. Global Sustain 7:e19. https://doi.org/10.1017/sus.2023.25
6. Chaudhary A, Burivalova Z, Koh LP, Hellweg S (2016) Impact of forest management on species richness: global meta-analysis and economic trade-offs. Sci Rep 6(1):23954. https://doi.org/10.1038/srep23954
7. Chazdon RL, Broadbent EN, Rozendaal DM, Bongers F, Zambrano AMA, Aide TM, Poorter L (2016) Carbon sequestration potential of second-growth forest regeneration in the Latin American tropics. Sci Adv, 2(5), e1501639
8. https://doi.org/10.1126/sciadv.1501639
9. Chen C, Park T, Wang X, Piao S, Xu B, Chaturvedi RK, Fuchs R, Brovkin V, Ciais P, Fensholt R, Tømmervik H (2019) China and India lead in greening of the world through land-use management. Nat Sustain 2(2):122–129. https://doi.org/10.1038/s41893-019-0220-7
10. Churkina G, Organschi A, Reyer CP, Ruff A, Vinke K, Liu Z, Reck BK, Graedel TE, Schellnhuber HJ (2020) Buildings as a global carbon sink. Nat Sustain 3(4):269–276. https://doi.org/10.1038/s41893-019-0462-4
11. Ciais P, Chevallier F, Wang Y, Lauerwald R (2026) Lateral Accounting of Transport in Terrestrial Ecosystems (LATTE): A high-resolution global land-atmosphere CO2 flux dataset from 1961 to 2022 for atmospheric inversions and carbon budgeting studies. https://essopenarchive.org/doi/full/10.22541/essoar.177170483.34963512. Authorea Preprints
12. Daigneault A, Baker JS, Guo J, Lauri P, Favero A, Forsell N, Johnston C, Ohrel SB, Sohngen B (2022) How the future of the global forest sink depends on timber demand, forest management, and carbon policies. Glob Environ Change 76:102582. https://doi.org/10.1016/j.gloenvcha.2022.102582
13. EEA (2025) Annual European Union greenhouse gas inventory 1990–2023 and inventory document 2025. EEA/PUBL/2025/024
14. https://unfccc.int/sites/default/files/resource/EU%20NID%202025.pdf
15. den Elzen MG, Dafnomilis I, Forsell N, Fragkos P, Fragkiadakis K, Höhne N, Kuramochi T, Nascimento L, Roelfsema M, van Soest H, Sperling F (2022) Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep Paris goals within reach. Mitig Adapt Strat Glob Change 27(5):33. https://doi.org/10.1007/s11027-022-10008-7
16. EPA (2024) Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022. U.S. Environmental Protection Agency, EPA 430-R-24-004. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022
17. Fang J, Chen A, Peng C, Zhao S, Ci L (2001) Changes in forest biomass carbon storage in China between 1949 and 1998. science, 292(5525), pp.2320–2322

18. https://doi.org/10.1126/science.1058629
19. FAO (2025) FAOSTAT. https://www.fao.org/faostat/en/#home (Accessed 10 September, 2025)
20. FAO (2020) Global Forest Resources Assessment 2020: Main report. Rome
21. https://doi.org/10.4060/ca9825en
22. Favero A, Daigneault A, Sohngen B, Baker J (2023) A system-wide assessment of forest biomass production, markets, and carbon. GCB Bioenergy 15(2):154–165. https://doi.org/10.1111/gcbb.13013
23. Favero A, Mendelsohn R (2017) The land-use consequences of woody biomass with more stringent climate mitigation scenarios. J Environ Prot 8:61–73
24. Franzen A, Mader S (2018) Consumption-based versus production-based accounting of CO2 emissions: is there evidence for carbon leakage? Environ Sci Policy 84:34–40. https://doi.org/10.1016/j.envsci.2018.02.009
25. Forsell N, Turkovska O, Gusti M, Obersteiner M, Elzen Mden, Havlik P (2016) Assessing the INDCs' land use, land use change, and forest emission projections. Carbon Balance Manag 11(1):26. https://doi.org/10.1186/s13021-016-0068-3
26. Forsell N, Chen M, Chang J, Zhao H, di Fulvio F (2024) Role of Harvested Wood Products in Meeting Long-term Climate Targets for China, vol 23. FORMATH, pp 23–003
27. Fuller MR, Baker JS, Daigneault A, Guo J, Lauri P, Favero A, Forsell N, Johnston C, Sohngen B (2025) Global carbon storage in harvested wood products: a forest sector model inter-comparison. Environmental Research Letters, 20(11), p.114021
28. https://doi.org/10.1088/1748-9326/ae0ce0
29. Fricko O, Havlik P, Rogelj J, Klimont Z, Gusti M, Johnson N, Kolp P, Strubegger M, Valin H, Amann M, Ermolieva T (2017) The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Glob Environ Change 42:251–267. https://doi.org/10.1016/j.gloenvcha.2016.06.004
30. Fyson CL, Jeffery ML (2019) Ambiguity in the land use component of mitigation contributions toward the Paris Agreement goals. Earths Future 7(8):873–891
31. Geng A, Yang H, Chen J, Hong Y (2017) Review of carbon storage function of harvested wood products and the potential of wood substitution in greenhouse gas mitigation. For Policy Econ 85:192–200. https://doi.org/10.1016/j.forpol.2017.08.007
32. Government of China (2018) The People's Republic of China Second Biennial Update Report on Climate Change. Beijing, China
33. Government of China (2019) Forest Resources in China - The 9th National Forest Inventory. National Forestry and Grassland Administration. Beijing, China
34. Government of China (2021) China's Mid-Century Long-Term Low Greenhouse Gas
35. Emission Development Strategy Beijing, China

36. Government of China (2023) The People's Republic of China's Third Biennial Update Report on Climate Change. Beijing, China
37. Government of China (2024) The People's Republic of China's Biennial Transparency Report on Climate Change. Beijing, China
38. Government of China (2025) The People's Republic of China's 2035 National Determined Contributions. Beijing, China
39. Grassi G, House J, Dentener F, Federici S, Elzen D, M., Penman J (2017) The key role of forests in meeting climate targets requires science for credible mitigation. Nat Clim Change 7(3):220–226. https://doi.org/10.1038/nclimate3227
40. Green C, Avitabile V, Farrell E, Byrne K (2006) Reporting harvested wood products in national greenhouse gas inventories: Implications for Ireland. Biomass Bioenerg 30(2):105–114. https://doi.org/10.1016/j.biombioe.2005.11.001
41. Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, Fargione J (2017) Natural climate solutions. Proceedings of the National Academy of Sciences, 114(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114
42. Havlík P, Schneider UA, Schmid E, Böttcher H, Fritz S, Skalský R, Aoki K, Cara S, De, Kindermann G, Kraxner F, Leduc S, McCallum I, Mosnier A, Sauer T, Obersteiner M (2011) Global land-use implications of first and second generation biofuel targets. Energy Policy 39(10):5690–5702. https://doi.org/10.1016/j.enpol.2010.03.030
43. Havlík P, Valin H, Herrero M, Obersteiner M, Schmid E, Rufino MC, Mosnier A, Thornton PK, Böttcher H, Conant RT, Frank S, Fritz S, Fuss S, Kraxner F, Notenbaert A (2014) Climate change mitigation through livestock system transitions. Proceedings of the National Academy of Sciences, 111(10), 3709–3714. https://doi.org/10.1073/pnas.1308044111
44. Harper AB, Powell T, Cox PM, House J, Huntingford C, Lenton TM, Shu S (2018) Land-use emissions play a critical role in land-based mitigation for Paris climate targets. Nat Commun 9(1):2938. https://doi.org/10.1038/s41467-018-05340-z
45. Head M, Bernier P, Levasseur A, Beauregard R, Margni M (2019) Forestry carbon budget models to improve biogenic carbon accounting in life cycle assessment. J Clean Prod 213:289–299. https://doi.org/10.1016/j.jclepro.2018.12.122
46. Hertwich EG (2021) Increased carbon footprint of materials production driven by rise in investments. Nat Geosci 14(3):151–155. https://doi.org/10.1038/s41561-021-00690-8
47. Hua E, Li S, Chen M, Forsell N (2025) How reference scenario selection affects technical mitigation potential at the sub-national level: Evidence from China's agricultural non-CO2 greenhouse gas emissions. J Clean Prod 523:146356
48. https://doi.org/10.1016/j.jclepro.2025.146356
49. IPCC (2003) Good Practice Guidance for Land-Use, Land-Use Change and Forestry. Prepared by the National Greenhouse Gas Inventories Programme (IGES)
50. IPCC (2006) IPCC Guidelines for National Greenhouse Gas Inventories—A Primer (IPCC)

51. https://doi.org/10.1029/2019EF001190
52. IPCC (2013) Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol
53. IPCC (2019a) Special Report on Climate Change and Land. Summary for Policymakers. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems
54. IPCC (2019b) 2019 Refinement to the 2006. IPCC Guidelines for National Greenhouse Gas Inventories
55. IPCC (2022) Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change
56. Ji C, Cao W, Chen Y, Yang H (2016) Carbon balance and contribution of harvested wood products in China based on the production approach of the intergovernmental panel on climate change. Int J Environ Res Public Health 13(11):1132. https://doi.org/10.3390/ijerph13111132
57. Johnston CM, Radeloff VC (2019) Global mitigation potential of carbon stored in harvested wood products. Proceedings of the National Academy of Sciences, 116(29), pp.14526–14531. https://doi.org/10.1073/pnas.1904231116
58. Ke S, Qiao D, Zhang X, Feng Q (2021) Changes of China's forestry and forest products industry over the past 40 years and challenges lying ahead. For policy Econ 123:102352. https://doi.org/10.1016/j.forpol.2020.102352
59. Kriegler E, Bauer N, Popp A, Humpenöder F, Leimbach M, Strefler J, Baumstark L, Bodirsky BL, Hilaire J, Klein D, Mouratiadou I (2017) Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. Glob Environ Change 42:297–315. https://doi.org/10.1016/j.gloenvcha.2016.05.015
60. Lamb WF, Gasser T, Roman-Cuesta RM, Grassi G, Gidden MJ, Powis CM, Minx JC (2024) The carbon dioxide removal gap. Nat Clim Change 14(6):644–651
61. https://doi.org/10.1038/s41558-024-01984-6
62. Lauri P, Forsell N, Korosuo A, Havlík P, Obersteiner M, Nordin A (2017) Impact of the 2 C target on global woody biomass use. For Policy Econ 83:121–130
63. http://dx.doi.org/10.1016/j.forpol.2017.07.005
64. Lesiv M, Schepaschenko D, Buchhorn M, See L, Dürauer M, Georgieva I, Jung M, Hofhansl F, Schulze K, Bilous A, Blyshchyk V (2022) Global forest management data for 2015 at a 100 m resolution. Scientific Data, 9(1), p.199
65. https://doi.org/10.1038/s41597-022-01332-3
66. Li B, Xu X, Liu X, Shi Q, Zhuang H, Cai Y, He D (2023) An improved global land cover mapping in 2015 with 30 m resolution (GLC-2015) based on a multisource product-fusion approach. Earth Syst Sci Data 15(6):2347–2373
67. https://doi.org/10.5194/essd-15-2347-2023

68. Liu D, Chen Y, Cai W, Dong W, Xiao J, Chen J, Zhang H, Xia J, Yuan W (2014) The contribution of China's Grain to Green Program to carbon sequestration. Landscape Ecol 29(10):1675–1688. https://doi.org/10.1007/s10980-014-0081-4
69. Lu F, Hu H, Sun W, Zhu J, Liu G, Zhou W, Zhang Q, Shi P, Liu X, Wu X, Zhang L (2018) Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. Proceedings of the National Academy of Sciences, 115(16), pp.4039–4044. https://doi.org/10.1073/pnas.1700294115
70. Ludvig A, Braun M, Hesser F, Ranacher L, Fritz D, Gschwantner T, Jandl R, Kindermann G, Ledermann T, P¨olz W, Schadauer K, Schmid BF, Schmid C, Schwarzbauer P, Weiss G, Wolfslehner B, Weiss P (2021) Comparing policy options for carbon efficiency in the wood value chain: Evidence from Austria. J Clean Prod 292:125985. https://doi.org/10.1016/j.jclepro.2021.125985
71. Lun F, Li W, Wang Z, Bai Y, Yang Y (2012) Spatio-temporal changing analysis on carbon storage of harvested wood products in China. Acta Ecol Sin 32:2918–2928. https://doi.org/10.5846/stxb201103210348
72. Luo C, Li S, Hua E, Forsell N, Chen M (2024) Synthesizing mitigation ambitions and implementation of the agriculture, forestry, and other land use (AFOLU) sector. Ecosystem Health and Sustainability, 10, p.0217. https://doi.org/10.34133/ehs.0217
73. Martin PA, Newton AC, Pfeifer M, Khoo M, Bullock JM (2015) Impacts of tropical selective logging on carbon storage and tree species richness: A meta-analysis. For Ecol Manag 356:224–233. https://doi.org/10.1016/j.foreco.2015.07.010
74. Mishra A, Humpenöder F, Churkina G, Reyer CP, Beier F, Bodirsky BL, Schellnhuber HJ, Lotze-Campen H, Popp A (2022) Land use change and carbon emissions of a transformation to timber cities. Nature communications, 13(1), p.4889
75. https://doi.org/10.1038/s41467-022-32244-w
76. Pauliuk S, Heeren N, Berrill P, Fishman T, Nistad A, Tu Q, Wolfram P, Hertwich EG (2021) Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. Nature communications, 12(1), p.5097
77. https://doi.org/10.1038/s41467-021-25300-4
78. Petersen AK, Solberg B (2005) Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. For policy Econ 7(3):249–259
79. https://doi.org/10.1016/S1389-9341(03)00063-7
80. Rockström J, Gaffney O, Rogelj J, Meinshausen M, Nakicenovic N, Schellnhuber HJ (2017) A roadmap for rapid decarbonization. Science 355(6331):1269–1271
81. https://doi.org/10.1126/science.aah3443
82. Roe S, Streck C, Obersteiner M, Frank S, Griscom B, Drouet L, Fricko O, Gusti M, Harris N, Hasegawa T, Hausfather Z (2019) Contribution of the land sector to a 1.5 C world. Nat Clim Change 9(11):817–828. https://doi.org/10.1038/s41558-019-0591-9

83. Rogelj J, Popp A, Calvin KV, Luderer G, Emmerling J, Gernaat D, Tavoni M (2018) Scenarios towards limiting global mean temperature increase below 1.5 C. Nat Clim change 8(4):325–332. https://doi.org/10.1038/s41558-018-0091-3
84. Rogelj J, Hare W, Chen C, Meinshausen M (2011) Discrepancies in historical emissions point to a wider 2020 gap between 2°C benchmarks and aggregated national mitigation pledges. Environmental Research Letters, 6(2), p.024002
85. https //10.1088/1748-9326/6/2/024002
86. Rüter S, Werner F, Forsell N, Prins C, Via E, Levet A-L (2016) ClimWood 2030, climate benefits of material substitution by forest biomass and harvested wood products: perspective 2030– final report. Johann Heinrich von Thünen-Institut, Braunschweig, p 142
87. Sato A, Nojiri Y (2019) Assessing the contribution of harvested wood products under greenhouse gas estimation: accounting under the Paris Agreement and the potential for double-counting among the choice of approaches. Carbon Balance Manag 14(1):15
88. https://doi.org/10.1186/s13021-019-0129-5
89. Sathre R, O'Connor J (2010) Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environ Sci Policy 13(2):104–114
90. https://doi.org/10.1016/j.envsci.2009.12.005
91. SFA (2024) The State Forestry Administration of the People's Republic of China. China Forestry Statistical Yearbooks. China Forestry Publishing House
92. Skog KE, Nicholson GA (1998) Carbon cycling through wood products: the role of wood and paper products in carbon sequestration. For Prod J 48(7):75–83
93. Smith S, Geden O, Gidden M, Lamb W, Nemet G, Minx J, Vaughan N (2024) The state of carbon dioxide removal. http://eprints.lse.ac.uk/id/eprint/129120
94. UNFCCC (2025) Nationally determined contributions under the Paris Agreement. Synthesis report by the secretariat. https://unfccc.int/sites/default/files/resource/cma2025_08.pdf
95. Werner F, Taverna R, Hofer P, Richter K (2005) Carbon pool and substitution effects of an increased use of wood in buildings in Switzerland: first estimates. Ann For Sci 62(8):889–902. https://doi.org/10.1051/forest:2005080
96. Werner F, Taverna R, Hofer P, Thürig E, Kaufmann E (2010) National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. Environ Sci Pol 13(1):72–85. https://doi.org/10.1016/j.envsci.2009.10.004
97. Yang H, Zhang X (2016) A rethinking of the production approach in IPCC: its objectiveness in China. Sustainability 8(3):216. https://doi.org/10.3390/su8030216
98. Yayla A, Mason AR, Wang J, van Ewijk S, Myers RJ (2025) Global wood harvest is sufficient for climate-friendly transitions to timber cities. Nat Sustain 8(9):1013–1025. https://doi.org/10.1038/s41893-025-01605-w

99. Yu Z, Ciais P, Piao S, Houghton RA, Lu C, Tian H, Agathokleous E, Kattel GR, Sitch S, Goll D, Yue X (2022a) Forest expansion dominates China's land carbon sink since 1980. Nature Communications, 13(1), p.5374
100. https://doi.org/10.1038/s41467-022-32961-2
101. Yu Z, Zhang H, Tu Q, Yang H (2022b) Methodological comparison of the production approach 2013 and 2019 for quantifying the carbon stock in harvested wood products in China. Front Environ Sci 10:758857. https://doi.org/10.3389/fenvs.2022.758857
102. Zhang L, Sun Y, Song T, Xu J (2019) Harvested wood products as a carbon sink in China, 1900–2016. Int J Environ Res Public Health 16(3):445. https://doi.org/10.3390/ijerph16030445
103. Zhang X, Chen J, Dias AC, Yang H (2020) Improving carbon stock estimates for in-use harvested wood products by linking production and consumption—a global case study. Environ Sci Technol 54(5):2565–2574. https://doi.org/10.1021/acs.est.9b05721
104. Zhang X, Yang H, Chen J (2018) Life-cycle carbon budget of China's harvested wood products in 1900–2015. For Policy Econ 92:181–192. https://doi.org/10.1016/j.forpol.2018.05.005
105. Zhang L, Zhang S, Chen D, Li T, Wang S, Xu Z, Wang Y, Liu Z, Zhang S (2023) Spatiotemporal trends of carbon stock in wood and bamboo products in China during 1987–2020. Sci Rep 13(1):15194. https://doi.org/10.1038/s41598-023-41007-6
106. Zhao H, Chang J, Havlík P, van Dijk M, Valin H, Janssens C, Ma L, Bai Z, Herrero M, Smith P, Obersteiner M (2021) China's future food demand and its implications for trade and environment. Nat Sustain 4(12):1042–1051. https://doi.org/10.1038/s41893-021-00784-6
107. Zhao X, Mignone BK, Wise MA, McJeon HC (2024) Trade-offs in land-based carbon removal measures under 1.5 C and 2 C futures. Nat Commun 15(1):2297
108. https://doi.org/10.1038/s41467-024-46575-3

Figures

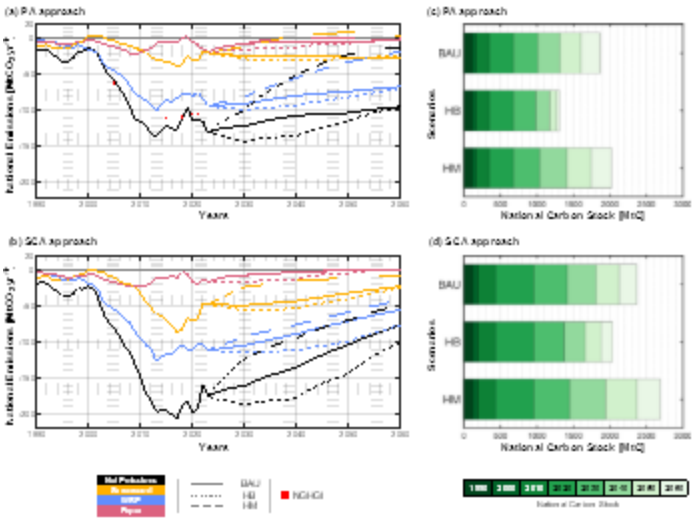


Figure 1

National development of the net HWP flux [$MtCO_2$] and HWP carbon stock following the PA and SCA approaches under the BAU, HB and HM scenarios. (a) Net HWP flux following the PA approach and compares the estimates with China's NGHGI estimates. The NGHGI estimates for 2005, 2020 and 2021 are from China's First BTR (Government of China, 2024), the 2015 estimate is from China's 2nd BUR (Government of China, 2018), and the 2018 estimate is from China's 3rd BUR (Government of China, 2023). (b) Net HWP flux following the SCA approach. (c) Nation HWP carbon stock [MtC] following the PA approach. (c) Nation HWP carbon stock [MtC] following the SCA approach.

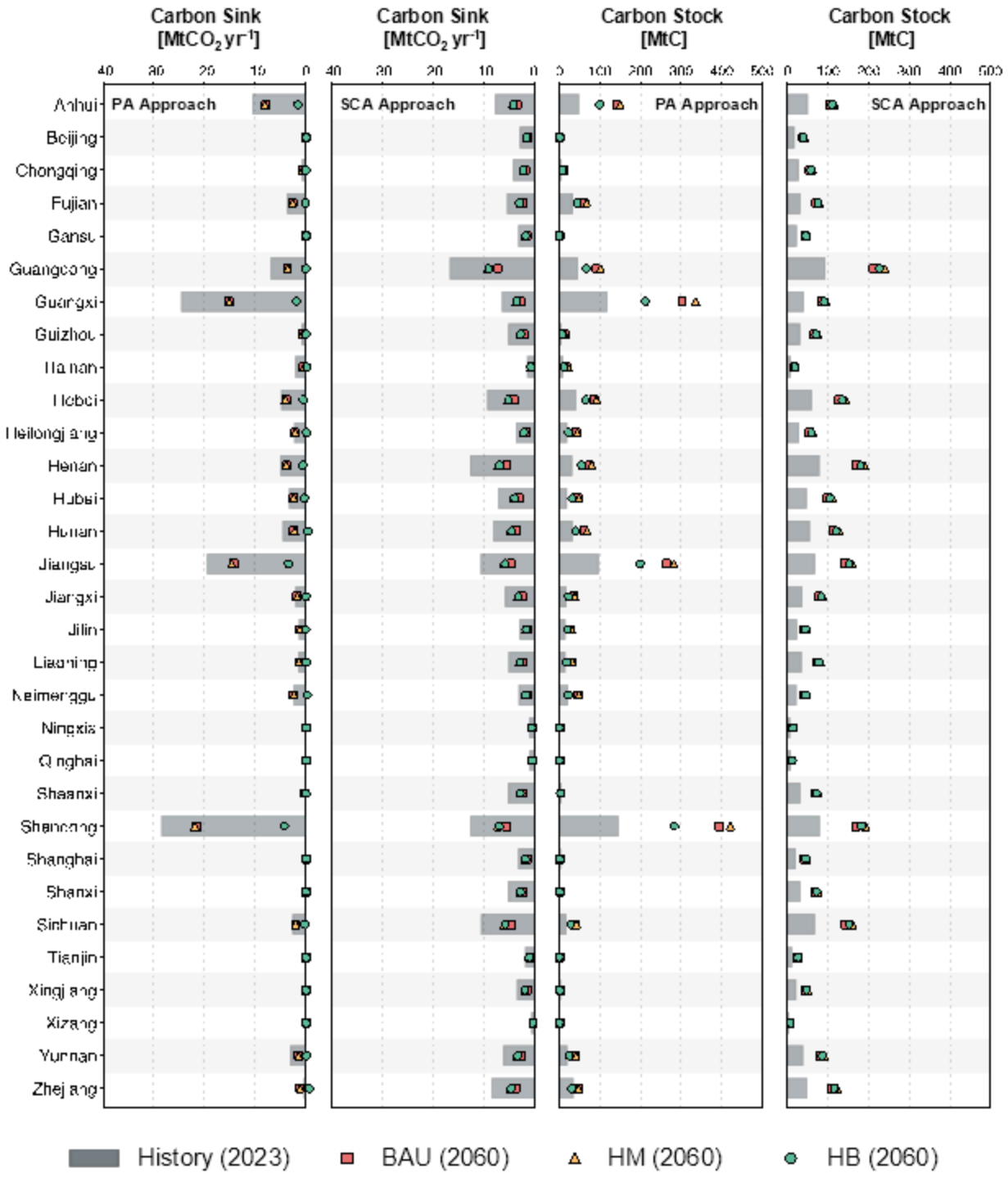


Figure 2

Province-level development of the HWP carbon sink [$MtCO_2\ yr^{-1}$] and HWP carbon stock [MtC] following the PA and SCA approaches for 2023, BAU, HB and HM scenarios.

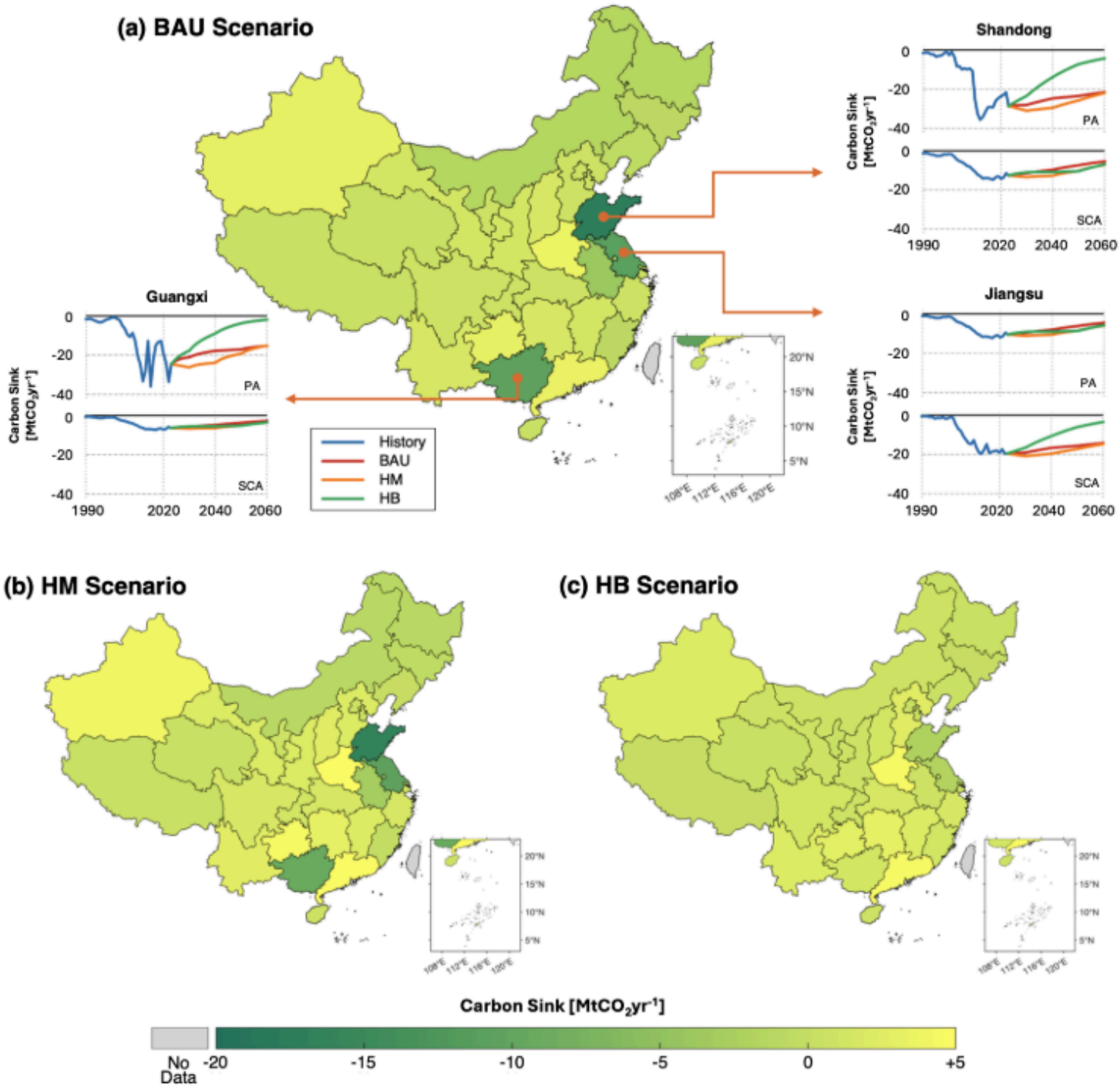


Figure 3

Differences in 2060 provincial HWP carbon sink [$MtCO_2\ yr^{-1}$] between the PA and SCA approaches for the BAU scenario, and development of the HWP carbon sink from 1990 to 2060 for the BAU, HB and HM scenarios for the provinces of Shandong, Jiangsu and Guangxi. A negative value indicates that the sink is larger for the PA than the SCA approach.

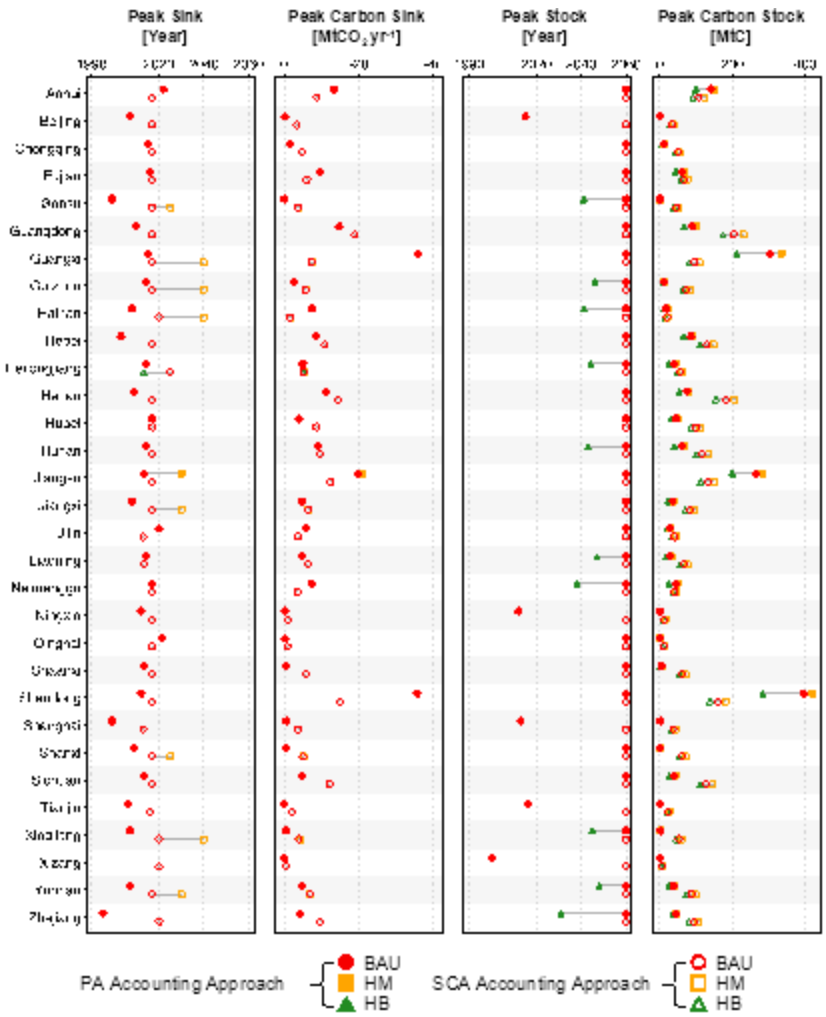


Figure 4

Province-level peak HWP sink [year], peak HWP stock [year], peak HWP carbon sink [$MtCO_2\ yr^{-1}$], and peak HWP carbon stock [MtC] for the BAU, HB and HM scenarios and following the PA and SCA approaches. Values for the HB and HM scenario that are consistent with the BAU scenario are now shown in the figure to enhance its clarity.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementaryinformation.docx