https://doi.org/10.5194/essd-2023-309
Preprint. Discussion started: 24 August 2023

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National forest carbon harvesting and allocation dataset for the period 2003 to 2018

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Abstract. Forest harvesting is one of the anthropogenic activities that most significantly affect the carbon budget of forests. However, the absence of explicit spatial information on harvested carbon poses a huge challenge in assessing forest harvesting impacts, as well as the forest carbon budget. This study utilized provincial-level statistical data on wood harvest, the tree cover loss (TCL) dataset, and a satellite-based vegetation index to develop a Long-term harvEst and Allocation of Forest Biomass (LEAF) dataset. The aim was to provide the spatial location of forest harvesting with a spatial resolution of 30 m and quantify the post-harvest carbon dynamics. The validations against the surveyed forest harvesting at 133 cities and counties indicated a good performance of the LEAF dataset in capturing the spatial variation of harvested carbon, with a coefficient of determination (R^2) of 0.83 between the identified and surveyed harvested carbon. The linear regression slope was up to 0.99. Averaged from 2003 to 2018, forest harvesting removed 68.34 Mt C yr^{-1}, of which more than 80% was from selective logging. Of the harvested carbon, 22%, 45%, 4%, and 29% entered the wood fuel, wood products, paper products, and residual pools, respectively. Direct combustion of wood fuel was the primary source of carbon emissions after wood harvest. However, carbon can be stored in wood products for a long time, and by 2100, almost 90% of the harvested carbon during the study period will still be retained. This dataset is expected to provide a foundation and reference for estimating the forestry and national carbon budgets. The 30 m × 30 m harvested carbon dataset from forests in China can be downloaded at https://doi.org/10.6084/m9.figshare.23641164.v2 (Wang et al., 2023).

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1. Introduction

As a critical terrestrial ecosystem type, forests play a pivotal role in regulating the global carbon cycle (Dixon et al., 1994). Over the period 2001 to 2019, global forests sequestrated 2.07 Gt C yr^{-1} from the atmosphere (Harris et al., 2021), contributing more than 70% of the global terrestrial sink (Friedlingstein et al., 2022). Forests also provide numerous important ecosystem services to society (Costanza et al., 1997), which may substantially impact the forest carbon sink (Lal et al., 2013). One of the most important services is the provision of wood products (Deal and White, 2012), which results in the transfer of carbon from forest ecosystems into the social system. The carbon harvested from forests is typically transferred into the pool of harvested wood products (HWPs) through their use of wood for construction, furniture (i.e., wood products), and fine papers (i.e., paper products), among others. These products are eventually decomposed and emitted into the atmosphere with different turnover times (IPCC, 2014, 2019a). For example, when harvested wood is used to make paper, the carbon within the paper decomposes and returns to the atmosphere within several years (Brunet-Navarro et al., 2017). On the contrary, the harvested carbon entering the wood products used in construction has a slow turnover rate and can be stored for many years (Brunet-Navarro et al., 2017). Previous studies have highlighted the large uncertainty in estimating carbon emissions of wood post-harvest due to a lack of information about the proportion of wood entering into various wood pools (Skog et al., 2004).

In China, forests are playing an increasingly important role in terrestrial carbon sinks benefiting from long-term afforestation projects (Liu et al., 2014). A recent study based on satellite data revealed that China is one of the few countries experiencing persistent greening over the past decades (Chen et al., 2019; Yuan et al., 2019). Unlike India, where croplands dominates greening, nearly half of China's greening comes from forests (Chen et al., 2019). However, despite these positive trends, China ranks as the second-largest timber consumer and the largest wood importer globally (Research and Market, 2019). In 2017, the consumption of wood in China reached 192.5 million cubic meters, with 43.6% of that consumption being supplied by domestic harvests (Research and Market, 2019). A previous study has highlighted that harvesting is the primary cause of forest disturbance in China, accounting for 85% of the average annual forest loss (Curtis et al., 2018). However, the impacts of forest harvesting on the terrestrial carbon cycle has not been estimated yet due to a lack of available data on harvested carbon. Accurate forest harvesting data are crucial for measuring the national carbon sink-source balance, an important

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component of national carbon budget analysis related to forest resources and wood utilization (Winjum, et al., 1997).

Although some efforts have been made, there are still large uncertainties in estimating harvested carbon in forest ecosystems (Hurtt et al., 2011, 2020). For example, the Land-Use Harmonization 2 (LUH2) dataset provides annual harvested biomass carbon data from primary and secondary forests (Hurtt et al., 2011, 2020). However, the spatial resolution of the LUH2 dataset (0.25°× 0.25°) is too coarse to analyze the dynamics of forest ecosystems at the regional or local scales, and its performance in assessing carbon harvest has not been examined in China. In addition, to our knowledge, no studies have been conducted to quantify the proportion of harvested wood or carbon entering into various wood pools, which is crucial for estimating carbon emissions returning to the atmosphere (Skog et al., 2004; Johnston and Radeloff, 2019). Over the past decades, construction, papermaking, and furniture manufacturing have shown substantial changes in China (Zhang et al., 2019; FAO, 2023), largely influencing the proportion of harvested carbon among various wood pools and the magnitude of emissions.

In this study, we developed a Long-term harvEst and Allocation of Forest Biomass (LEAF) dataset to provide: (1) the spatial location of harvested carbon with a high resolution of 30 m; (2) the proportion of harvested carbon allocated into various wood pools; and (3) the lagged carbon emissions of harvested carbon from the aforementioned wood pools. The tree cover loss (TCL) dataset developed by Hansen et al. (2013) and the interannual variation of a satellite-based vegetation index were used to determine the location of harvested carbon, and the provincial statistical biomass storage provided by the China Forestry and Grassland Statistical Yearbook was used to quantify the magnitude of harvested carbon. Post-harvest carbon dynamics were estimated based on a first-order decay (FOD) function according to the post-harvest wood use provided by the statistical data (IPCC, 2014, 2019a).

2. Methods and Materials

2.1 Method of calculating harvested carbon

This study aimed to generate a Long-term harvEst and Allocation of Forest Biomass (LEAF) dataset, which is a component of the Terrestrial Ecosystem Disturbance (TED) dataset, referred to as TED-LEAF. We aimed to identify two types of forest harvesting: clear-cutting and selective logging (Fig. 1). For

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clear-cutting, the location was determined using the TCL dataset produced by Hansen et al. (2013). The TCL dataset indicates stand replacement disturbance or the complete removal of tree cover canopy at a scale of 30 m × 30 m. It has been widely used to identify deforestation globally or in multiple regions (Hansen et al., 2013; Curtis et al., 2018). To calculate the harvested carbon from clear-cutting, it was necessary to determine the above-ground biomass carbon (AGB, t C) storage for each pixel. Only the 9th National Forest Inventory (NFI) provided both provincial forest AGB density (CD, t C ha^{-1}) and forest area (S, ha). Then, we calculated pixel-level (30 m × 30 m) AGB storage for 2014 to 2018 as:

$$AGB_j = CD \times S \times \frac{NDVI_j}{SNDVI} \tag{1}$$

where AGB_j indicates the AGB of the jth forest pixel in a given province and year; $NDVI_j$ denotes the Normalized Difference Vegetation Index (NDVI) of the jth forest pixel in that province for that year; $SNDVI$ is the sum of NDVI of all forest pixels in that province for that year. According to the province-level biomass storage (V, m^3) provided by the 6th to 8th NFIs covering 1998 to 2013 at 5-year intervals, this study used the following method to calculate pixel-level (30 m × 30 m) AGB storage for 2003 to 2013:

$$AGB_j = V \times \frac{NDVI_j}{SNDVI} \times Coef \tag{2}$$

where $Coef$ (t C m^{-3}) is the coefficient that converts biomass storage (V) to biomass carbon (AGB). Combining the provincial forest biomass storage (V_9, m^3) from the 9th NFI, we calculated the provincial $Coef$ (Table S1) as:

$$Coef = \frac{CD \times S}{V_9} \tag{3}$$

Then, the harvested carbon was calculated for all pixels corresponding to clear-cutting derived from the TCL dataset. The total harvested carbon from clear-cutting (HC_C, t C) in a given province can be calculated by aggregating all pixels occurring tree cover loss.

For selective logging, we developed a satellite-based method to identify the location and magnitude of selective logging. The method was based on the principle of multitemporal satellite-based vegetation index analysis and detected the changes of NDVI between two adjacent years. This approach relied on two fundamental assumptions. First, we assumed that NDVI values decreased resulting from selective logging. Therefore, we calculated the NDVI difference ($NDVI_{diff}$) between the current year ($NDVI_t$) and subsequent year ($NDVI_{t+1}$) at all pixels (Eq. (4)) and determined the possible logging locations with decreased $NDVI_{diff}$, where $NDVI_{diff} < 0$ indicated potential selective logging.

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$$NDVI_{diff} = NDVI_{t+1} - NDVI_t \tag{4}$$

Second, we assumed that the reductions in NDVI values resulting from selective logging would be more significant compared to decreases caused by other factors such as droughts, heat waves, ice storms, and insect outbreaks (Yuan et al., 2014), without considering fires due to their low frequency in China (Curtis et al., 2018). Changes in vegetation coverage caused by logging activities were expected to have a drastic and rapid impact on ecosystems compared to other environmental changes and disturbances. Therefore, the decreased magnitude of NDVI values due to selective logging was assumed to be the largest. Based on this assumption, we can identify potential selective logging areas by focusing on pixels exhibiting larger $NDVI_{diff}$. For a specific province, all pixels with negative $NDVI_{diff}$ values were sorted by ascending order in $NDVI_{diff}$. The pixels at the front of the sorted list had more negative $NDVI_{diff}$ values and a larger likelihood of being logging locations. Thereby, a threshold of $NDVI_{diff}$ ($NDVI_{Th}$) was needed to distinguish selective logging from other disturbed pixels. Selective logging was considered to have occurred only when $NDVI_{diff} < NDVI_{Th}$. Then, the harvested carbon (HC_S, tC) was calculated in all pixels corresponding to selective logging according to Eq. (5):

$$HC_{s\ j} = \frac{NDVI_{diff\ j}}{NDVI_j} \times AGB_j \tag{5}$$

Therefore, the province-level statistical harvested carbon (SHC) was used to determine the $NDVI_{Th}$ of each province, which made the sum of HCc and HCs equal to SHC. Theoretically, the determined $NDVI_{Th}$ should be less than 0. However, in several provinces, when $NDVI_{Th}$ was set to 0, the sum of HC_C and HC_S (identified harvested carbon) was still lower than SHC (e.g., Anhui), implying that the identified harvested carbon was underestimated. Then we assigned the unidentified harvested carbon ($S-HC_C-HC_S$) to pixels where selective logging occurred.

$$HC_{s1\ j} = (S - HC_C - HC_S) \times \frac{NDVI_{diff\ j}}{SNDVI_{diff}} \tag{6}$$

where $HC_{S1\ j}$ is the harvested carbon added by the jth pixel where selective logging occurred; $NDVI_{diff\ j}$ indicates the $NDVI_{diff}$ of the jth pixel, and $SNDVI_{diff}$ is the sum of $NDVI_{diff}$ of all pixels where selective logging occurred in that province. This approach increased the harvested carbon for all pixels where selective logging occurred, so we also examined whether the harvested carbon exceed their AGB at the pixel scale. If so, we counted these pixels as clear-cutting. To assess the accuracy and validity of the dataset, we additionally quantified the proportion of pixels with harvested carbon exceeding their AGB compared to the total number of harvested pixels at the province level.

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In addition, this study assumed that forest harvesting did not occur in the National Nature Reserves and high-altitude regions because of high transport costs and harvesting expenses. For the Tibetan Plateau and Yunnan Province, we assumed no harvesting at elevations higher than 2,500 m. In the other provinces, harvesting was assumed to be absent at elevations higher than 1,500 m, according to Nabuurs et al., (2019).

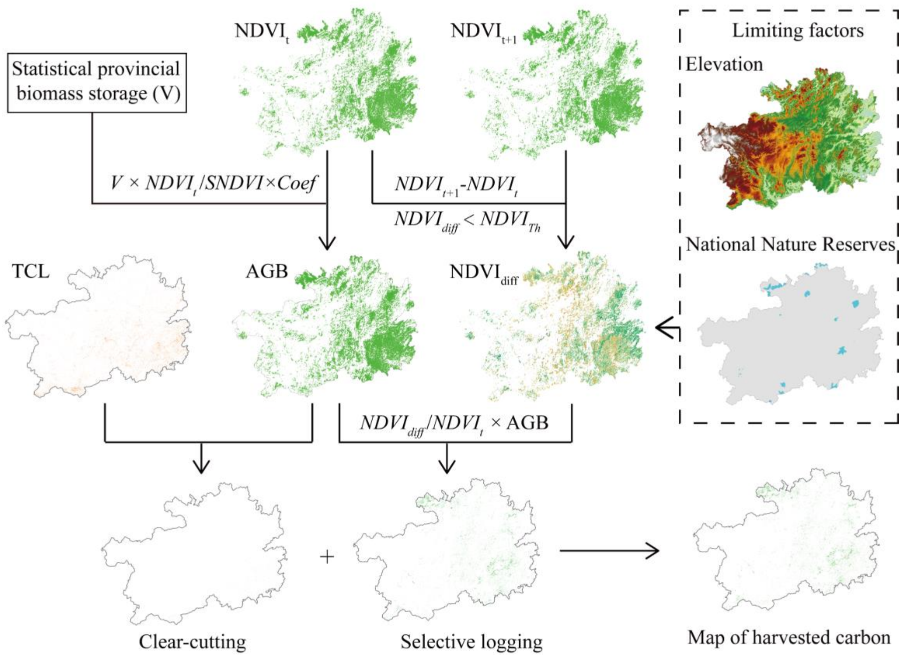

Figure 1: Flowchart for mapping forest carbon harvesting.

2.2 Annual carbon changes from HWPs in-use and end-use

The harvested wood was allocated into four wood pools. (1) Wood fuel pool, where the wood was burned for fuel, resulting in immediate carbon emissions through combustion. (2) Paper and (3) wood products pool (i.e., HWPs pools), where the carbon will remain stored until the products are either retired from use or reach the end of their lifespan and are consequently discarded. Subsequently, these discarded products are either directed to solid waste disposal sites (SWDS), where they decompose, or are incinerated (Stockmann et al., 2012; IPCC, 2019a, 2019b). In this study, the lifespan of paper products and wood products were assumed to be 5 and 100 years (IPCC, 2019a), respectively, and we calculated the delayed emissions to 2100. Waste incineration is currently more common in developed countries, while in China, landfills remain the primary method of disposal (Cai et al., 2018; IPCC, 2019b). (4)

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Residual pool, including losses from primary processing during conversion from harvested wood to lumber and discarded poor quality wood, which would be left on site or used as wood fuel (Lippke et al., 2011; Stockmann et al., 2012). It is difficult to obtain the percentage of discarded wood products and residual wood to be decomposed or incinerated. We assumed all of the discarded wood products were deposited to SWDS, which were decomposed, and all of the residual wood was treated as wood fuel for combustion.

2.2.1 Annual carbon changes in "HWPs in use"

Carbon stocks and decays from in-use HWPs were calculated using the methodologies for estimating carbon removal from HWPs described in the "2006 IPCC Guidelines for National Greenhouse Gas Inventories" (IPCC, 2006) and the "2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol" (IPCC, 2014). "Decay" in this paper refers to the discarding of wood and paper products from end uses (and sent to SWDS), not biological decay. Moreover, here we focused on the carbon fate of wood harvested in China, the imports and exports were not considered. The FOD method (Pingoud and Wagner, 2006) was used to estimate the carbon change in the two pools of in-use wood products and in-use paper products as:

$$C(i+1) = e^{-k} \times C(i) + \left[\frac{(1-e^{-k})}{k}\right] \times Inflow(i) \quad (7)$$

$$\Delta C(i) = C(i+1) - C(i) \quad (8)$$

where i denotes the year; $C(i)$ is the carbon stock in the HWPs pool at the beginning of year i; and k ($k = ln(2)/HL$) is the decay constant (yr^{-1}). HL is the half-life of the HWPs pool in years, which refers to the number of years it takes to lose half of the existing material in the pool. k for paper products and wood products were taken as 0.347 and 0.023, respectively, according to the IPCC default values (IPCC, 2014). $Inflow(i)$ is the inflow to the HWPs pool during year i, and $\Delta C(i)$ represents the carbon stock change of the HWPs pool during year i. Next, the amount of discarded organic carbon (DOC) deposited in the SWDS, as the wood or paper products go out of use in year i, was calculated using Eq. (9):

$$DOC_i = Inflow(i) - \Delta C_i \quad (9)$$

2.2.2 Annual carbon changes in solid waste disposal sites (SWDS)

The DOC deposited in SWDS was divided into three parts, (1) DOC for aerobic decomposition (DOC_{ar}), producing CO_2 until all available oxygen has been used up; (2) DOC for anaerobic

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decomposition (DOC_{an}), producing both CH_4 and CO_2; (3) *DOC* that will not be decomposed but stored long-term in the SWDS (DOC_{ls}).

The DOC_{ar} was calculated as:

$$DOC_{ar_i} = DOC_i \times f_{ar} \tag{10}$$

where f_{ar} denotes the proportion of *DOC* undergoing aerobic decomposition. The disposal of waste products in China aligns with the "unmanaged-deep" category in the SWDS (Zhang et al., 2019), and the f_{ar} was assumed to be 0.2 (IPCC, 2019a). The DOC_{ar_i} undergoes aerobic decomposition and releases as CO_2 in year *i*:

$$CO_{2\,ar_i} = DOC_{ar_i} \times \frac{44}{12} \tag{11}$$

The DOC_{an} is calculated with Eq. (12), as:

$$DOC_{an_i} = DOC_i \times (1 - f_{ar}) \times DOC_f \tag{12}$$

where DOC_f indicates the fraction of *DOC* that can be decomposed under anaerobic conditions, with values of 0.5 and 0.1 for paper products and wood products (IPCC, 2019a), respectively. The annual carbon change of DOC_{an} in the SWDS was calculated according to the FOD method (Pingoud and Wagner, 2006).

$$DOC_{an\,a_i} = DOC_{an_i} + DOC_{an\,a_{i-1}} \times e^{-k} \tag{13}$$

$$DOC_{an\,decomp_i} = DOC_{an\,a_{i-1}} \times (1 - e^{-k}) \tag{14}$$

where $DOC_{an\,a_i}$ represents the DOC_{an} accumulated in the SWDS at the end of year *i*; $DOC_{an\,decomp_i}$ denotes DOC_{an} decomposed in the SWDS in year *i*; the anaerobic decomposition generally occurs in the following year of deposition. *k* ($k = ln(2)/HL$) is the decay constant (yr^{-1}). Considering the environmental conditions of SWDS in China (Lou et al., 2015; Cai et al., 2018), *k* for paper waste and wood waste were taken as 0.05 and 0.025, respectively (IPCC, 2019a). Then, the potentials to generate CH_4 and CO_2 from the anaerobic decomposition of DOC_{an} were:

$$CH_{4_i} = DOC_{an\,decomp_i} \times F \times \frac{16}{12} \tag{15}$$

$$CO_{2\,an_i} = \left[DOC_{an\,decomp_i} \times (1 - F)\right] \times \frac{44}{12} \tag{16}$$

where CH_{4_i} and $CO_{2\,an_i}$ are CH_4 and CO_2 produced by anaerobic decomposition in SWDS in year *i*. *F* denotes the volume fraction of CH_4 in the generated landfill gas, and the IPCC default value of 0.5 is encouraged (IPCC, 2019a). We assumed that there was no recovery and oxidation of CH_4 and that the landfill gas will all be released into the atmosphere. The total CO_2 decomposed from *DOC* in year *i* was

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the sum of $CO_{2\,ar_i}$ and $CO_{2\,an_i}$. The CH_4 emissions were transformed to CO_2 equivalents (CO_2e) to harmonize calculations of the overall global warming potential (IPCC, 2007).

The DOC_{ls} can be calculated as:

$$DOC_{ls_i} = DOC_i - DOC_{ar_i} - DOC_{an_i} \quad (17)$$

Then, the carbon stock in the SWDS at the end of year *i* was calculated as:

$$DOC_{s_i} = \sum_0^i DOC_{ls_i} + DOC_{an\,a_i} \quad (18)$$

2.3 Datasets

2.3.1 National Forest Inventories

The National Forest Inventories (NFIs) provided nine periods of provincial biomass storage for 1973-1976, 1977-1981, 1984-1988, 1989-1993, 1994-1998, 1999-2003, 2004-2008, 2009-2013, and 2014-2018 (National Forestry and Grassland Administration, 2019). We used the biomass storage data during the 6th-9th NFIs to generate the distribution of AGB for 2003-2018.

2.3.2 Statistical forest harvesting data

The annual provincial wood output, extracted from the China Forestry and Grassland Statistical Yearbook, was categorized into two main types: commercial and non-commercial wood. Commercial wood was further divided into simply logs, processed lumber, lumber for paper, fuel wood, and others, whereas lumber for wood products (such as furniture, construction lumber, etc.) was calculated as total commercial wood minus the lumber for paper and fuel. Non-commercial wood included the volume of timber logged (T_{log}) by farmers for burning and for their personal consumption. Commercial wood refers to lumber output (L_{output}), not the actual logging volume (L_{log}). L_{log} refers to the total volume of wood cut and removed from the forest, regardless of whether it was further processed into commercial lumber. L_{output} refers to the volume of wood that can be used for further production and sale after preliminary processing (such as peeling, sawing, etc.). Meanwhile, this process may eliminate some unusable or poor-quality wood, the L_{output} is generally less than the L_{log}. Based on the provincial lumber rates (R, i.e., the ratio of L_{output} to L_{log}) provided by China's timber production plan from the National Bureau of Statistics (Table S1), we calculated the actual annual L_{log} of commercial wood for each province as:

$$L_{log} = \frac{L_{output}}{R} \quad (19)$$

Then, the total harvested carbon (i.e., the SHC in Sect. 2.1) for a given province was calculated as:

$$SHC = \left(L_{log} + T_{log}\right) \times Coef \qquad (20)$$

2.3.3 Surveyed forest harvesting data

The surveyed forest harvesting data, i.e., the harvested volume at the city and county-level, was retrieved from the official website of each provincial Forestry Bureau. To ensure the effective implementation of the forest harvesting quota system, the provincial Forestry Bureau randomly selects several cities and/or counties, conducting comprehensive field inspections of the annual forest harvesting. The actual annual harvest volume of a specific city or county is determined through comprehensive cross-validation of multiple methods, including declaration and approval records reviewing, on-site measurements, and remote sensing monitoring, etc. These techniques are employed to ensure the accuracy and reliability of the obtained harvest data. There were 133 records nationwide available from 2006 to 2018, concentrated in the provinces of Guizhou, Yunnan, Zhejiang, and Sichuan (Fig. S1).

2.3.4 Forest cover map

The Chinese Forest Cover Dataset, reconstructed by fusing the NFIs and twenty Land Use and Land Cover datasets, was used as the forest cover base map. This forest cover accurately depicts the historical changes in China's forest cover in the period of 1980-2015, with overall accuracy from 76.9% to 99.4% (Xia et al., 2023).

2.3.5 Satellite-based vegetation index

The NDVI dataset from 2000 to 2020 calculated by Dong et al (2021) was applied to allocate AGB and identify selective logging. This NDVI dataset was calculated using all Landsat5/7/8 remote sensing data for the whole year, the NDVI maxima in each image year were obtained by data pre-processing and data smoothing (Dong et al., 2021).

2.3.6 Mask data

This study used the elevation and National Nature Reserves to exclude the regions where rarely occur harvesting. The elevation dataset was obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/) and the distribution of National Nature Reserves was provided by the National Earth System Science Data Center, National Science &

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Technology Infrastructure of China (http://www.geodata.cn).

2.4 Accuracy assessment

The surveyed forest harvesting data at city and county-level were employed to validate the accuracy of the LEAF dataset by conducting a comparison with the estimated harvested carbon. The relationships between the estimated harvested carbon and the corresponding surveyed harvested carbon were assessed by linear regression. Then the coefficient of determination (R^2) and slope of linear regression can be calculated, and the closer these two values are to 1, the better the estimates.

3. Results

3.1 Accuracy evaluation of LEAF dataset

Accuracy evaluation of the LEAF dataset generated from this study showed good performance in indicating spatial variations of harvested carbon in China. This study used province-level statistical harvested carbon to determine the threshold for identifying selective logging and used city and county-level surveyed harvested carbon ranging from 2006 to 2018 to examine the performance. The estimated harvested carbon showed high consistency with surveyed harvested carbon, with R^2 of 0.83 and a linear regression slope of 0.99 (Fig. 2).

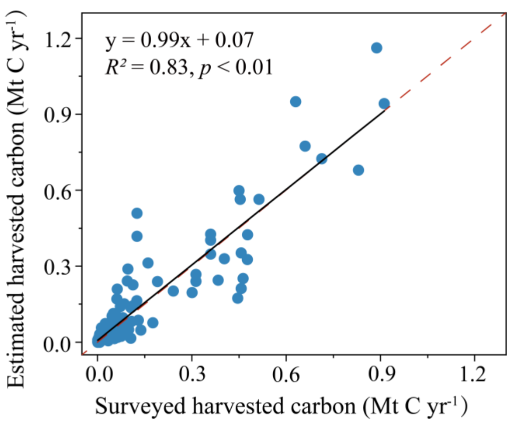

Figure 2: Comparison of estimated and surveyed harvested carbon from the official website of each provincial forestry bureau at the city and county levels across all investigated provinces. The solid line indicates the regression lines, and the red dashed line indicates the 1:1 line.

The validation also showed the performance of the LEAF dataset across various provinces and

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periods. The dataset exhibited excellent skill in simulating the spatial variation of harvested carbon across all surveyed provinces, with R^2 between estimates and surveyed data ranging from 0.24 to 0.96 (Fig. S2). Zhejiang performed the best (Fig. S2e), while Sichuan's performance was relatively low, with R^2 less than 0.5 (Fig. S2c). The LEAF dataset also effectively reproduced the spatial variations of harvested carbon across different periods, with R^2 values ranging from 0.31 to 0.99 (Fig. S3). The estimates for 2013 and 2017 demonstrated superior performance, with both linear regression slopes approximating 1 (Fig. S3c and g). However, except for 2016, estimates from other periods displayed varying degrees of underestimation or overestimation (Fig. S3).

3.2 Spatial and temporal patterns of harvested carbon in China

There was a large heterogeneity in harvested carbon over the regional scale. Harvesting mainly occurred in Eastern and Southern China, and rarely in Northwest China (Fig. 3a and b). Guangxi Province recorded the highest harvested carbon, constituting approximately 30% of China's annual total harvested carbon. This volume is 2.5 times larger than that of Fujian, the province with the second highest harvested carbon (Fig. 3c). In terms of harvesting ways, over 80% of the nationwide clear-cutting harvested carbon originated from Guangxi, Guangdong, Fujian, Yunnan, and Jiangxi (Fig. 3c). Forest harvesting in Jiangxi, Guangdong, Yunnan, and Hainan was dominated by clear-cutting, in these provinces, harvested carbon from clear-cutting comprised more than 50% of the total harvested carbon (Fig. 3c, Fig. 4a). For other provinces, selective logging was the main way of forest harvesting (Fig. 4b).

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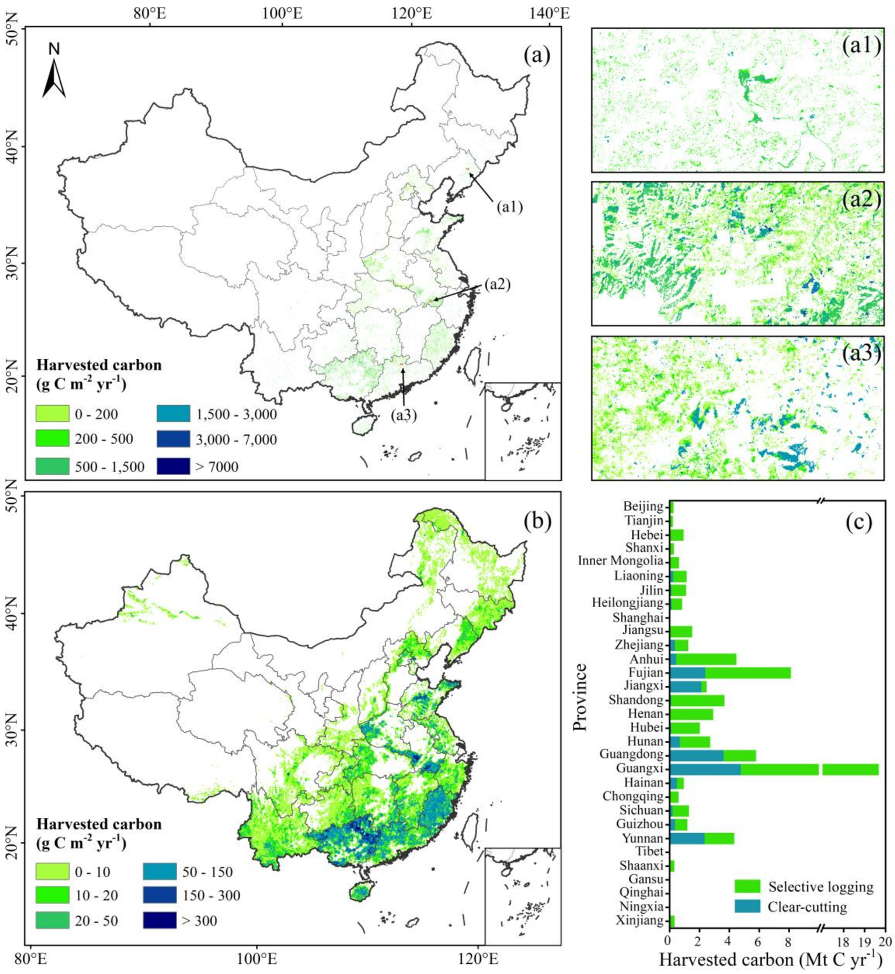

Figure 3: Map of forest harvested carbon for China in 2016 at (a) 30 m and (b) 0.1°resolution and the zoomed-in view of the example areas of (a) (a1, a2, and a3), (c) shows the harvested carbon from clear-cutting and selective logging by province in 2016.

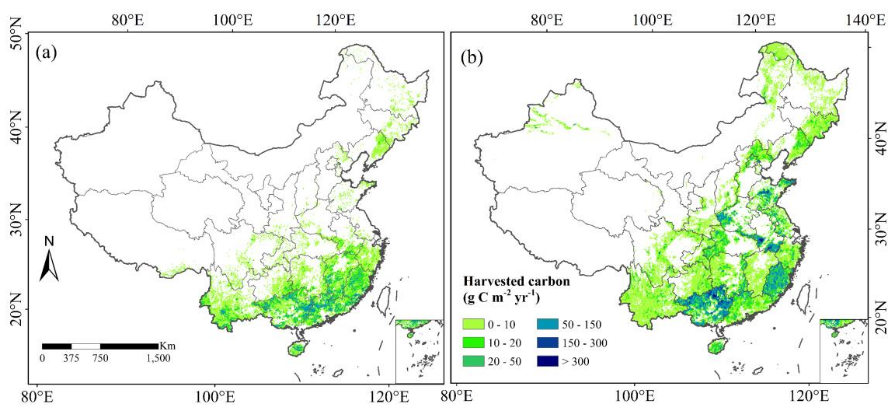

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Figure 4: Map of forest harvested carbon from (a) clear-cutting and (b) selective logging for China in 2016 at 0.1°resolution.

China experienced an overall upward trend in forest carbon harvesting, with average harvesting of 68.34 Mt C yr^{-1} from 2003 to 2018 (Fig. 5). The most substantial growth in harvested carbon was observed from 2003 to 2008, increasing approximately 1.6 times from 49.75 Mt C yr^{-1} in 2003 to 79.54 Mt C yr^{-1} in 2008 (Fig. 5). Among all surveyed years, the harvested carbon peaked in 2008, primarily driven by an uptick in wood fuel harvest (Fig. 6). In subsequent years, the harvested carbon generally plateaued, with minor fluctuations. Selective logging was the main way of forest harvesting (Fig. 5). Averaged from 2003 to 2018, there was 55.63 Mt C yr^{-1} from selective logging, accounting for around 82% of the total harvested carbon (Fig. 5). Nevertheless, the proportion of harvested carbon from clear-cutting was overall on the rise, reaching its peak in 2012 when it constituted 30% of the total harvested carbon for that year (Fig. 5).

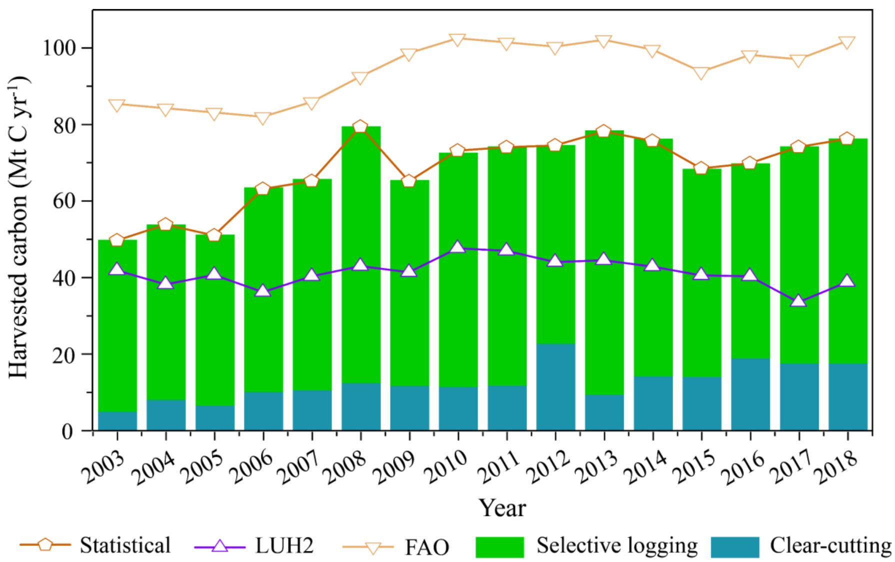

Figure 5: Long-term changes of harvested carbon in China between 2003 and 2018 from statistical, LUH2, FAO, and LEAF datasets.

3.3 Allocation of harvested carbon into the various wood pools

This study also provides the allocation of harvested carbon into the various wood pools with different lifetimes, including wood fuel pool, wood products pool, paper products pool, and residual pool (Sect. 2.2). Averaged from 2003 to 2018, over the entire China, harvested carbon was allocated into four

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pools with 22%, 45%, 4%, and 29%, respectively (Fig. 6). Timber for wood products mainly came from Southern China, with Guangxi contributing an average of 16.6% of the national timber for wood products annually, followed by Fujian (9.6%). Meanwhile, Guangxi also contributed up to 42.7% of the wood used for paper production (Fig. 7). Over 50% of the wood in Fujian was used for wood fuel, contributing nearly 30% of the national wood fuel. Similar to Fujian, more than 50% of the wood in Yunnan was used for wood fuel, making Yunnan the second-largest province in terms of wood supply for wood fuel (Fig. 7). From 2003 to 2018, wood harvesting has been increasing, while wood for fuel has been decreasing, with its share decreasing from 31% to 16%. More wood was used to produce wood and paper products; however, wood in residual pool was also increasing (Fig. 6).

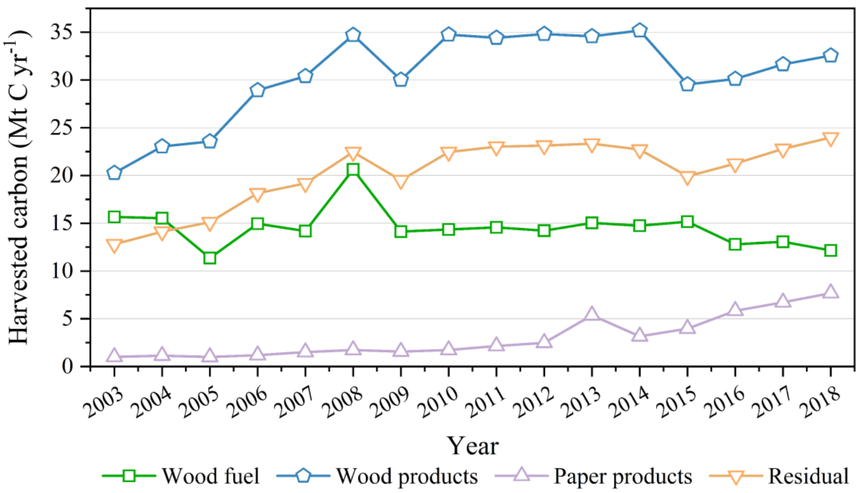

Figure 6: Long-term changes of different pools of harvested carbon from 2003 to 2018 in China.

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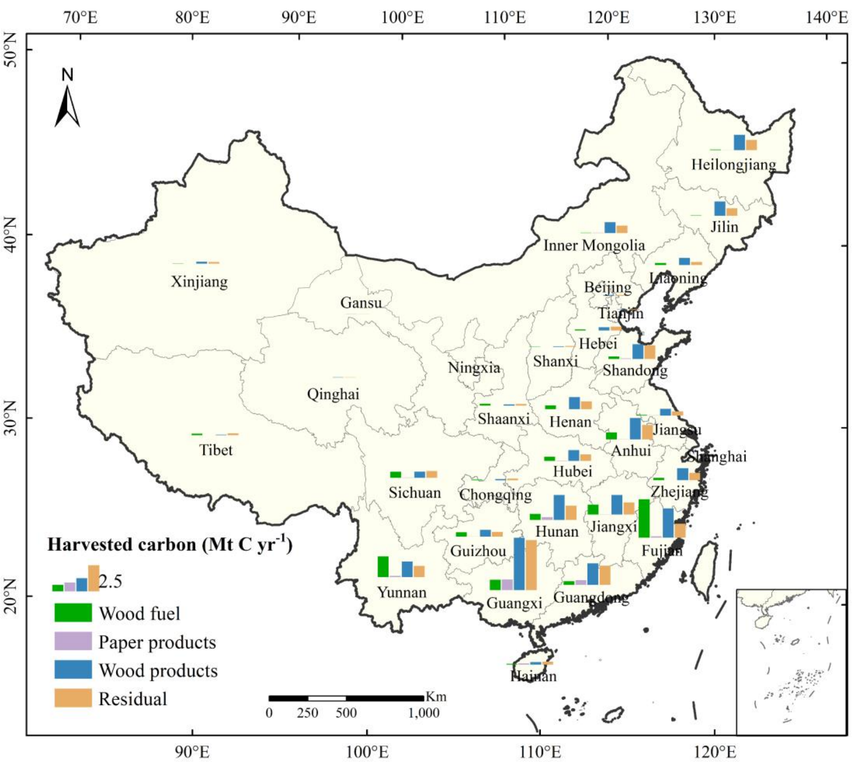

Figure 7: Pools of provincial harvested carbon averaged from 2003 to 2018.

We further quantified the delayed emissions of harvested carbon in various pools. Combustion of wood fuel resulted in major carbon emissions, and wood products contributed a major share of carbon stock (Fig. 8). Wood fuel was typically burned for a short period of time (1 year), resulting in average emissions of 55.1 Mt CO_2e yr^{-1} from 2003-2018 (Fig. 8a). Additionally, discarded or retired paper and wood products that enter SWDS undergo gradual decomposition, releasing an average of 3.9 Mt CO_2e yr^{-1} and 8.9 Mt CO_2e yr^{-1}, respectively, from 2003 to 2100 (Fig. 8a). The total carbon stock sustained an upward trend, peaking at 530 Mt C in 2018 (Fig. 8b). As products are discarded and/or retired, the carbon stock in currently used products persistently declines without ongoing wood inputs. Furthermore, most of the waste products that enter SWDS do not decompose and become a permanent carbon sink (Fig. 8b). About 90% of harvested carbon during 2003-2018 will still be stored in the wood products by 2100 (Fig. 8b).

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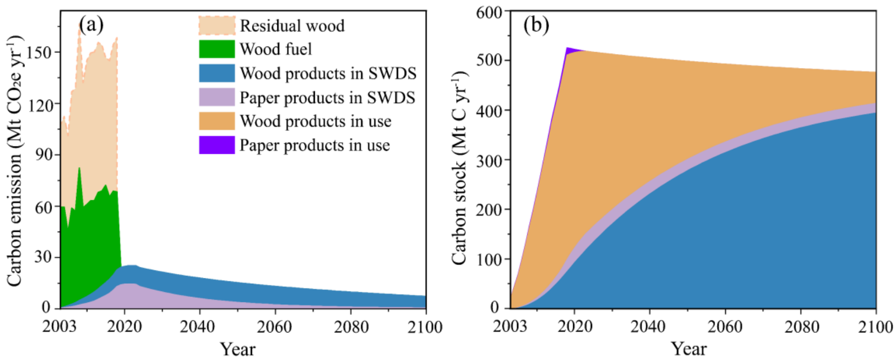

Figure 8: Annual (a) carbon emissions (b) and stock of harvested wood in-use and end-use.

4. Discussion

4.1 Implications for simulating the carbon sink in China

Forest harvesting is one of the most important human activities determining the terrestrial ecosystem carbon budget (Liu et al., 2011; Pan et al., 2011). Forest harvesting largely decreases the leaf area index, increases litter biomass, and alters stand temperature and moisture, strongly impacting the structure and function of ecosystems (Nepstad et al., 1999; Liu et al., 2011; Jian et al., 2022). Harvesting causes damage to the forest canopy and soils, leading to temporary increases in litter carbon stock. It ultimately results in a net loss of soil carbon due to the damages inflicted on the forest canopy and soil. Following a disturbance, soil carbon loss can exceed carbon gain in above-ground biomass (Kowalski et al., 2004). Pennock and van Kessel (1997) found that soil carbon decreased by 5 to 20 t C ha^{-1} over a 20-year period following clear-cutting, a significant loss compared to the carbon accumulated in a maturing forest's biomass (Pennock and Van Kessel, 1997).

Forest harvesting is a type of human activity that cannot be simulated by ecosystem modeling. Therefore, the development of regional and global datasets is necessary for quantifying the impacts of forest harvesting. The LUH2 dataset is an important source of data for indicating global forest harvesting and has been widely used to simulate the impacts of forest harvesting on the terrestrial carbon sink (Harper et al., 2018; Hurtt et al., 2020; Friedlingstein et al., 2022). However, our results showed that the LUH2 dataset underestimated harvested carbon by about 38.5% on average for China, compared with the statistical data (Fig. 5, Fig. S4). The LUH2 dataset used national wood volume harvest data from the Food and Agriculture Organization (FAO, 2020), which were allocated to the pixels where tree cover lost

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(Hurtt et al., 2020). Across all of China, the harvested carbon data from the FAO were approximately 40% higher compared to the statistical data averaged from 2003 to 2018. Nevertheless, after 2000, the spatial pattern of forest harvesting was constrained using the Landsat forest loss data (i.e., TCL) (Hansen et al., 2013) by verifying if the annualized gridded forest loss derived from the Landsat data matched the forest harvesting information in the LUH2 dataset. However, the TCL dataset only indicates clear-cutting and does not include selective logging. Our result showed that there was a large proportion of selective logging (Fig. 5), indicating that the LUH2 dataset largely underestimates the harvest area.

This study not only represents the temporal and spatial patterns of harvested carbon, but also provides the allocation of harvested carbon among the pools. Unlike harvested crop carbon, which will emit into the atmosphere at a faster rate, harvested forest carbon is stored in various HWPs pools, and emits back into the atmosphere with different lifetimes (Skog, 2008; IPCC, 2019a). As an extension of forest resources, the carbon dynamics of HWPs in use and after use have multiple impacts on national greenhouse gas (GHG) inventories (Johnston and Radeloff, 2019). Clarifying the proportion of post-harvest carbon allocated to different pools is the key to accurately assessing carbon dynamics. In addition, previous studies focused more on the carbon stored in HWPs (Stockmann et al., 2012; Matsumoto et al., 2022; Wei et al., 2023). However, the assessment of the global potential of HWPs as a carbon sink is subject to the balance between carbon inflows and outflows (Johnston and Radeloff, 2019). In particular, waste products emit non-CO_2 GHG such as CH_4, contributing to climate change (Cai et al., 2018). Moreover, the carbon emissions from harvested wood exhibit delayed and long-term effects. Previous studies rarely provided estimates of future carbon dynamics for HWPs (Heath et al., 2010; Zhang et al., 2019; Wakelin et al., 2020). Tracking the long-term dynamics of carbon and assessing the future climate mitigation potential can provide a better foundation for GHG management in the forestry sector.

4.2 Spatio-temporal changes of harvested carbon and allocation in China

The spatial heterogeneity of forest harvesting is influenced by the distribution of forest resources in China (Fig. 3). Intensive harvesting in Southern China (e.g., Guangxi and Fujian) indicates a demand for specific tree species, such as *Eucalyptus* and *Cunninghamia lanceolata* (Yu et al., 2020). As the total harvesting increased, both clear-cutting and selective logging exhibited a general upward trend (Fig. 5), mirroring the dynamic equilibrium in the allocation of harvesting ways across China's forests. The rate of increase in clear-cutting significantly outpaced that of selective logging (Fig. 5). A growing demand

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for timber is driving an upward in large-scale forest harvesting. Nevertheless, selective logging has remained the principal way of forest harvesting in China. Moreover, selective logging is a widely employed silvicultural practice that plays a central role in forest management worldwide (Liu et al., 2011). In the United States, the area covered by selective logging is approximately 61% of that occupied by clear-cutting (Masek et al., 2011). In Brazil, selective logging doubles the previous estimates of the total forest degraded by human activities (Asner et al., 2005). Selective logging is a more diffuse disturbance than forest clearance (Fisher et al., 2014) and is mostly invisible to satellites (Asner et al., 2005; Matricardi et al., 2010; Hethcoat et al., 2019). Despite many efforts to address the challenge of estimating selective logging using satellite data through image classification, it is still difficult to monitor low-intensity selective logging due to the coarse resolution of satellite imagery (Asner et al., 2005; Matricardi et al., 2010; Hethcoat et al., 2019). Objective spatially explicit reporting on selective logging is the basis for model-based assessment of the impact of forest harvesting on the carbon budget.

Forest harvesting in China continued to increase during the study period. However, the wood for fuel declined by nearly 23%, especially the harvesting for burning from farmers, contributing an average of nearly 70% of burned timber annually, decreased by nearly 35% (Fig. S5). This rapid decline in rural areas indicates that China is successful in the rural energy transition, benefiting the mitigation of air pollution and climate change (Chen et al., 2016; Tao et al., 2018). Production of wood and paper products in China was on the rise (Fig. 6), constituting a carbon pool that delays carbon release (Fig. 8). HWPs in use rarely emit carbon if there was no decay or combustion (e.g., building fire), being a stable carbon sink during their lifespan, especially wood used for construction (Profft et al., 2009; Churkina et al., 2020). Although the CO_2 emitted in SWDS is considered carbon neutral (Van Ewijk et al., 2020), CH_4 emissions from SWDS are detrimental to climate due to their higher global warming potential (IPCC, 2007). Promoting an increase in carbon storage and a reduction of carbon emissions can be achieved by extending the lifespan and improving the recycling rate of wood products (Brunet-Navarro et al., 2017). However, this approach may not be as effective for paper products, as they often have low or even negative recycling benefits (Van Ewijk et al., 2020). Therefore, recommendations in the wood sector prioritize allocating harvested wood to long-lasting products (Fortin et al., 2012; Smyth et al., 2014) and products with high recycling rates (Brunet-Navarro et al., 2016; Werner et al., 2010). Meanwhile, the increase of wood in the residue pool reflects inefficient processing and poor wood quality. Improving the efficiency of wood harvesting and processing processes, as well as enhancing forest ecological

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management, is also necessary for the reduction of carbon emissions.

4.3 Uncertainties of the LEAF dataset

Although the LEAF dataset demonstrated a good performance in capturing the spatial variability of harvested carbon in China, several potential uncertainties exist. First, the harvested carbon was found to be underestimated in several provinces over several years. Among the estimates covering a span of 16 years across 31 provinces, approximately 28% of them were underestimated, with the highest frequency of underestimation occurring in southern provinces (Fig. 9a). Compared to statistical values, the harvested carbon was underestimated by an average of 0.4-60.4% from 2003 to 2018 across these investigated provinces (Fig. 9b). Anhui Province had the highest degree of underestimation, with underestimation occurring in all years (Fig. 9). To avoid this underestimation, we assigned the unidentified harvested carbon to the pixels where selective logging occurred, increasing the harvested carbon of these pixels (Sect. 2.1, Eq. (6)), resulting in an estimation of more harvested carbon than the actual AGB at several pixels. We examined the number of pixels where the harvested carbon exceeded its AGB at the province level. The results showed that the number of pixels where harvested carbon exceeded its AGB was less than 2% of the number of pixels where harvesting occurred for each province annually (Fig, S6).

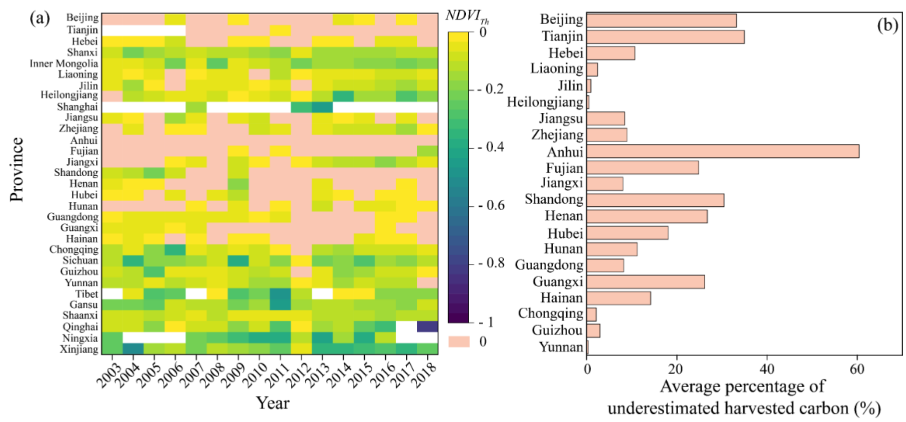

Figure 9: (a) Annual $NDVI_{diff}$ thresholds ($NDVI_{Th}$) for each province. An $NDVI_{Th}$ of 0 indicates that the province's harvested carbon was underestimated that year and a blank $NDVI_{Th}$ denotes that there was no harvesting in that province that year according to the statistics. (b) Average percentage of underestimated harvested carbon in the provinces where underestimation occurred from 2003 to 2018.

The underestimation of harvested carbon is closely related to the accuracy of identifying both selective logging and clear-cutting. The quality of selective logging identification largely depends on the quality and performance of NDVI. The accuracy is largely impacted by low data quality in cloudy and rainy southern areas. In addition, NDVI is sensitive to green vegetation cover but not dense vegetation (Huete et al., 2002), and begins to saturate over dense vegetation with AGB values higher than 25 t C ha^{-1} (Chang et al., 2023), contributing to the underestimation of AGB. Overlooking the continued growth of uncut vegetation within a pixel and the regional-scale climate impacts led to an underestimation of $NDVI_{diff}$. Consequently, the harvested carbon may be underestimated at regional scales, particularly in provinces with substantial forest coverage (e.g., Guangxi). The estimation of clear-cutting was primarily limited by the performance of the TCL dataset generated by Hansen et al. (2013). In subtropical and temperate regions, the producer's accuracy and user's accuracy of TCL are both approximately 80%, indicating that the dataset can identify tree cover loss with relatively high accuracy. However, there is still a 20% level of uncertainty (Hansen et al., 2013), and further efforts are needed to improve the identification of clear-cutting.

Second, the lack of specific information concerning the destiny, utilization, and longevity of harvested wood introduced several uncertainties in the allocation and carbon dynamics estimation of harvested carbon. It is virtually impossible to trace the trade patterns and lifetimes of wood after it has been harvested and sold (Profft et al., 2009). Information on the end products of harvested wood (i.e., tableware, furniture, columns, etc.) is unavailable, leading to rough estimates of wood destination and product lifetimes. In this study, all residual wood was assumed to be burned as wood fuel would induce an overestimation of carbon emissions. Meanwhile, this study ignored recycled wood products, which may extend the carbon storage in products (Brunet-Navarro et al., 2017), causing an underestimation of carbon stock in products in use. More efforts are needed to track the production and end use of the harvested wood, as they play a key role in the estimation of the effects on national GHG inventories (White et al., 2005; Johnston and Radeloff, 2019). Additionally, the decomposition of organic matter in SWDS is closely related to the management system and environmental conditions (Ximenes et al., 2015). Due to the lack of country-specific data, the parameters recommended by the IPCC were used. Obtaining more detailed parameters will help to more accurately assess the dynamics of harvested carbon on a national or even regional scale.

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5. Data availability

The 30 m × 30 m Long-term harvEst and Allocation of Forest Biomass (LEAF) dataset is available at https://doi.org/10.6084/m9.figshare.23641164.v2.(Wang et al., 2023).

The file format of the product is GeoTIFF with the spatial reference of WGS84 (EPSG:4326). Each GeoTIFF file represents annual harvested forest carbon (unit: g C $m^{-2}yr^{-1}$), the absolute harvested carbon per pixel is obtained by multiplying by the corresponding pixel area.

6. Conclusion

This study produced a Long-term harvEst and Allocation of Forest Biomass (LEAF) dataset, which provides spatial information on forest harvesting at a resolution of 30 m. The validation results demonstrated the accuracy and reliability of the LEAF dataset in capturing the spatial variation of harvested carbon. From 2003 to 2018, harvested carbon showed an increased trend. Additionally, our dataset showed that selective logging resulted in more than 80% of the total harvested carbon. The carbon taken away from forest harvesting was allocated to four wood pools, with the direct combustion of wood fuel as the primary source of carbon emissions after harvesting. However, it is important to highlight that the carbon stored in wood products has the potential for long-term retention. In summary, the development of the LEAF dataset enhances our understanding of the spatial patterns of forest harvesting and post-harvest carbon dynamics in China. The LEAF dataset generated by this study is an important data source for estimating the carbon budget of forest ecosystems in China, which can also provide essential insights for sustainable forest management and climate change mitigation efforts.

Author contributions

WY and DW designed the research, performed the analysis, and wrote the paper; PR, and XX performed the analysis; NF, ZQ, and XC edited and revised the manuscript.

Competing interests

The authors declare that they have no conflict of interests.

Financial support

This research was supported by the key project of the National Natural Science Foundation of China (42141020).

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