

# From carbon neutral to climate neutral

## Dynamic life cycle assessment for wood-based panels produced in China

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### Abstract

The forestry sector is crucial in supporting climate change mitigation, where the mitigation potential is assessed by combining forest carbon analysis and wood product life cycle assessment (LCA). Static LCA (sLCA) is the approach commonly used in national forestry mitigation models worldwide. Static GHG effects are calculated as a running total of emissions and removals, which are often used to imply climate effects. Also, carbon neutrality, a state when the GHG effects equal zero, is used to imply neutral climate effects. However, until carbon neutrality is achieved, the increased emissions contribute to climate warming. Dynamic LCA (dLCA) is an improved method to estimate climate effects by considering the atmospheric dynamics and heat trapping capacity of different GHGs. Climate neutrality is a state when the warming effects caused by increased emissions are fully compensated by warming reduction contributed by removals. We applied dLCA and sLCA to China-made wood-based panels produced from 1990 to 2018 by harvesting poplar plantations. Our results suggested that, compared to dLCA results, static GHG effects largely underestimated climate warming effects or overestimated mitigation contributions. Also, decades or longer was required to achieve climate neutrality following carbon neutrality, if achievable. So, within a given timeframe, a forestry mitigation activity can achieve carbon neutrality but increase climate warming, hindering the goal of limiting global temperature rise that was set in the 2015 Paris Agreement. Thus, to assess climate warming effects, using dLCA in addition to GHG effects is essential for forestry mitigation analysis.

### KEYWORDS

global warming effects, greenhouse gas effects, industrial ecology, poplar plantation, radiative forcing, static lifecycle assessment

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## 1 | INTRODUCTION

Climate change might be the biggest challenge humans have faced in generations. In the 2015 Paris Agreement, 195 countries agreed to act quickly to control the global average temperature rise to well below 2°C by 2100 to avoid irreversible effects (UNFCCC, 2015). The forestry sector (forest and wood products) has a unique role in climate change mitigation as wood products store carbon and the released carbon is resequenced in regenerating forests (Chen et al., 2014; Iordan et al., 2018). Estimates show that global wood products removed 335 million tonnes of carbon dioxide-equivalent (Mt CO<sub>2</sub>-eq) from the atmosphere in 2015, which may increase to 441 Mt CO<sub>2</sub>-eq per year by 2030 under certain socioeconomic developments (Johnston & Radeloff, 2019). Substituting greenhouse gas (GHG)-intensive materials by wood and using wood to produce energy will further reduce fossil fuel-based emissions (Eriksson et al., 2007; Sathre & O'Connor, 2010; Smyth et al., 2017).

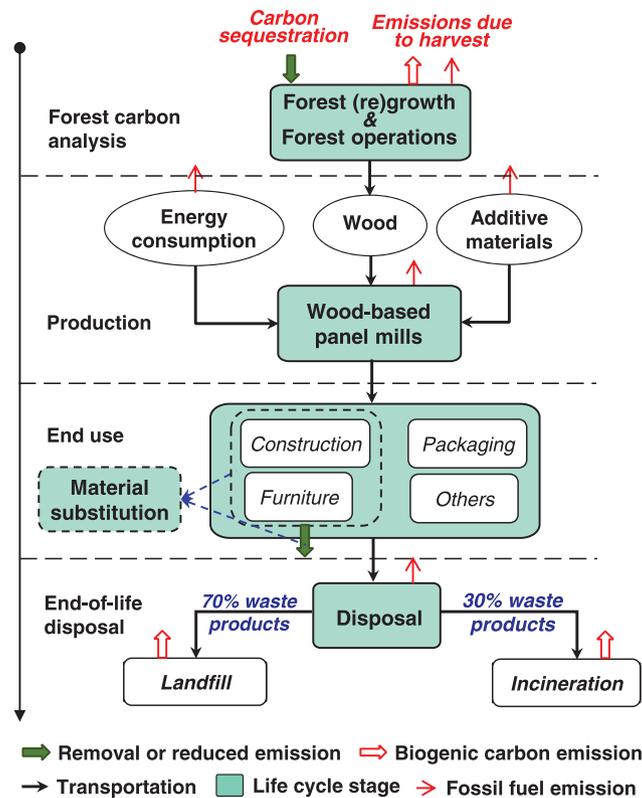
The mitigation benefits of wood products are partly determined by product life cycle, which can be highly dynamic depending on product type, production processes, end uses, and service lives (Earles et al., 2012; Faraca et al., 2019; Head et al., 2019, 2021). Hence, understanding the carbon dynamics of the wood product life cycle is highly relevant to forestry mitigation assessment (Garcia & Freire, 2014; Smyth et al., 2017). Life cycle assessment (LCA) has been widely used to quantify the environmental effects of the production and use of wood products (Gustavsson et al., 2017; Lan et al., 2020). In a large and rapidly expanding base of scientific literature, static LCA (sLCA), the most common LCA method, is used to assess the effects of wood products on atmospheric GHG concentrations (Sahoo et al., 2019). Using sLCA, all the forestry sector's annual emissions and removals by a given year are assumed to occur at the same time and are simply summed, and non-CO<sub>2</sub> emissions are converted to CO<sub>2</sub>-eq using their global warming potential (GWP) (IPCC, 2014).

More recent work has outlined the shortcomings of sLCA in handling the complex forestry sector carbon dynamics (Brandão et al., 2013; Breton et al., 2018; Cherubini et al., 2016; Head et al., 2020; Levasseur et al., 2010). In this study, the annual and cumulative net emissions or removals assessed using sLCA are referred to as "static GHG effects," while carbon neutrality is defined as a state when the emissions from forest harvesting and wood product life cycle are fully offset by carbon sequestration in regenerating forests and reduced emissions due to wood substitution (i.e., static carbon neutrality). Though the temporal aspects of the earlier-mentioned emissions and removals and their time-dependent climate effects are often not adequately considered (Røyne et al., 2016), static carbon neutrality is often used to imply neutral climate effects, and emission increases and reductions are assumed to equal increased and reduced climate warming effects, respectively (Cherubini et al., 2011; Helin et al., 2013). While relatively easy to calculate and understand, static GHG effects are not direct or accurate estimates of climate effects on relatively short time horizons (e.g., 100 years) (Brunet-Navarro et al., 2016; Johnson, 2009; Levasseur et al., 2016; Liu et al., 2018). A decades-long time lag often exists between the initially increased forestry sector emissions and net removals (Guest et al., 2013; Peñaloza et al., 2019; Ter-Mikaelian et al., 2015), so the increased emissions before carbon neutrality is achieved will contribute to atmospheric heat trapping. Also, GHG emissions occurring at different times result in different cumulative climate warming contributions for a given timeframe. Without considering these dynamic aspects, in the short term, using forestry sector static GHG effects to imply climate effects can lead to underestimated climate warming effects or overestimated mitigation contribution (Booth, 2018; Cherubini et al., 2011; Garcia et al., 2020; Zanchi et al., 2012). So, temporal trade-offs need to be analyzed based on the timeframe of a mitigation goal.

To overcome the shortcomings of sLCA, in the Fifth Assessment Report (IPCC, 2014), the Intergovernmental Panel on Climate Change (IPCC) recommended alternative metrics to replace the simple GWP. In a few recent studies, a dynamic LCA (dLCA) approach was proposed and used to consider the dynamic aspects of the forestry sector's emissions and removals, as well as their dynamic effects on climate warming (Fouquet et al., 2015; Levasseur et al., 2010, 2012). The cumulative emissions/removals assessed using dLCA is referred to in this study as "dynamic GHG effects," and we defined "climate neutrality" as a state when the increased radiative forcing caused by all emissions is fully offset by the reduced radiative forcing contributed by the removals. Here, radiative forcing is the change in the net, downward minus upward, radiative flux at the top of the atmosphere due to a change in a driver of climate change, such as atmospheric GHG concentrations (IPCC, 2014).

In the last decade or so, a handful of studies used dLCA to assess forestry mitigation potential. Kirkinen et al. (2008) used the ratio of solar energy absorbed in a given timeframe by the emissions from fuel production and combustion to producing a unit of energy. Cherubini et al. (2011) and Guest et al. (2013) developed a unit-based index for evaluating the global warming contributions from harvesting forests to produce energy. Pingoud et al. (2012) defined GWP factors as climate warming indicators to assess forest biomass use. Fouquet et al. (2015) compared the climate effects of wood-based and non-wood-based house construction in France. Peñaloza et al. (2016) estimated the climate change effects of increased use of wood products in construction in Sweden and Head et al. (2020, 2021) developed the GHG life cycle inventory and climate impact profiles for wood products used in construction in Canada. However, Brunet-Navarro et al. (2016) reviewed 41 wood product LCA models or forest carbon models developed worldwide, many of which are designed for conducting national and regional forestry sector mitigation assessment. In most of these models, explicit inclusion of climate effects is lacking, thus it remains an emerging research need (Brunet-Navarro, 2021).

As a major category of wood products, wood-based panels (WBP) include plywood, fiberboard, particleboard, and some other minor types. In 2018, the global production of WBP reached a peak of 408 million m<sup>3</sup>, representing 45.3% of global production of solid wood products; as the largest producer and consumer in the world, in this year China's WBP accounted for 49.9% of global production (FAO, 2019). In an earlier study, it was estimated that the carbon stocks of China's WBP in use and in landfills increased by 31.7 Mt CO<sub>2</sub> per year between 2008 and 2015, due to



**FIGURE 1** System boundary used to assess the net emissions or removals of the wood-based panel forestry sector in China (fossil fuel-based emissions from transportation of harvested wood and wood products were included in this study but are not illustrated here)

rapid increases in production (Wang et al., 2017). The production and use of China-made WBP may hugely affect atmospheric GHG concentrations, and thus need to be accurately assessed as part of mitigation efforts by the global forestry sector.

Previous investigations focused mostly on life cycle inventory of resource and energy consumption, emissions generated, and wood carbon allocation and conversion for producing a unit of a panel product (Hussain et al., 2017; Nakano et al., 2018; Taylor et al., 2017; Wilson, 2010). China-specific studies on GHG effects of WBP, as well as other types of wood products, are relatively scarce; a few published studies produced the static GHG effects of wood product use, often without considering the detailed product end uses and their lifespans (Lun et al., 2012; Wang et al., 2017; Zhang et al., 2018), or focusing on single product types. Also, studies combining wood products LCA with forest carbon simulation and assessing the consequent atmospheric GHG effects are lacking.

Using a dLCA approach, we quantified the GHG effects and the consequent global warming effects for China's WBP industry. This analysis was integrated with a carbon change analysis of the harvested forest to produce the required wood biomass to appropriately assess the GHG effects and the resulting climate change contributions (Cherubini et al., 2011; Knauf et al., 2015; McKechnie et al., 2011; Smyth et al., 2020). Substitution by wood products of emission-intensive materials in the construction and furniture sectors was also considered. The objectives of this study were to (a) assess the GHG effects and consequent global warming impacts of 1 m<sup>3</sup> of China-made plywood to illustrate the concepts of carbon and climate neutrality, (b) identify the relevant factors determining the GHG effects and climate change contributions of WBP, and (c) estimate the GHG effects and climate change contributions of China-made WBP from 1990 to 2018.

## 2 | METHODS

### 2.1 | Scope of the analysis

Figure 1 illustrates the assessment system boundary, which includes the forest harvested to produce WBP in China and the entire life cycle of these products. Fast-growing poplar plantations provided almost 60% of wood biomass used in WBP production in China in the last two decades or so (CNFPPIA, 2015). Due to a lack of data, another 40% of biomass used in WBP production was not considered. We included forest carbon stock changes due to harvesting and regenerating poplar forest to provide the required wood biomass for WBP manufacturing, while ignoring other biomass sources due to lack of information.

The life cycle of WBP consisted of the following three phases: (a) production—harvested wood was transported to the WBP mills to produce panel products in year 1; (b) end use—these products were divided among four end uses based on China-specific statistics: Construction, furniture production, packaging and shipping, and other uses; and (c) end-of-life—after reaching the end of their service lives, 70% of the wood products were disposed of in landfills and the remaining 30% were burned and the carbon immediately released as CO<sub>2</sub> (Zhang et al., 2018).

Assessment of the forestry sector's GHG effects and the consequent climate effects included the following components: (a) Emissions or removals reflected by changes in the forestry sector's carbon stocks (biogenic CO<sub>2</sub>) that were estimated using Equation (1) in Section 2.2.2; (b) fossil fuel-based emissions for producing WBP and the additional materials consumed to produce these products (CO<sub>2</sub> and CH<sub>4</sub>); (c) landfill CH<sub>4</sub> emissions from decomposing WBP disposed of in landfill (biogenic CO<sub>2</sub> emissions were reflected in (a)); (d) reduced GHG emissions by substituting WBP for GHG-intensive nonwood materials; and (e) an additional essential component, the climate effects (see next section) assessed as the radiative forcing effects caused by increased or reduced atmospheric GHG. The first four components are the inventory of the forestry sector's emissions and removals, which were used to estimate GHG effects using sLCA. And the fifth component was included in dLCA, in addition to the first four components, to evaluate the climate effects caused by increased or reduced emissions and the static GHG effects.

The analysis outlined earlier was first applied to 1 m<sup>3</sup> plywood to show the differences between sLCA and dLCA, illustrate the concepts of carbon neutrality and climate neutrality, and demonstrate the evaluation of climate effects. A 1-m<sup>3</sup> product analysis was relatively easier since the life cycle inventory data are often unit product-based, and using a simpler scenario may better illustrate these concepts. Through testing, a 100-year period was found appropriate to illustrate the analysis. We then conducted a similar analysis for the annual production of the three WBP products from 1990 to 2018 in China. We chose 1990 as the start year because WBP production in China was negligible before 1990 (Table S1) and it was about then that China began establishing large-scale poplar plantations.

## 2.2 | Development of a temporally differentiated inventory

We developed a temporally differentiated life cycle inventory for WBP produced in China, as described in Sections 2.2.1 and 2.2.2.

### 2.2.1 | Forest carbon analysis and life cycle assessment of wood-based panels

We used a forest growth model developed by Hou et al. (2020) to simulate the carbon stock changes in poplar plantations, which included equations specific to poplar plantation in China used to estimate gross volume (Equation S1) and live tree biomass carbon (Equations S2 and S3) based on forest age. Soil and forest floor were omitted from the calculation due to their negligible carbon stock changes over time. We defined a conceptual forest landscape that consisted of 13 stands ranging from 1- to 13-years-old in 1990, and assumed the forest was harvested at 13 years of age each year. A detailed description of forest carbon analysis is available in Section 2 of the Supporting Information.

The LCA of WBP consisted of emission and removal components described in Section 2.1. Detailed LCA methods are provided in Section 3 of the Supporting Information, while life cycle inventory data for China-made WBP are provided in Section 4 of the Supporting Information.

### 2.2.2 | Temporally differentiated inventory

The cumulative forestry sector biogenic carbon balance was produced using Equation (1) based on the forest and wood products carbon stock analysis, as described in Section 2.2.1:

$$C_{FS}(t) = FC_{\text{non-har}}(t) - [C_{\text{inuse}}(t) + C_{\text{landfill}}(t) + FC_{\text{har}}(t)] \quad (1)$$

in which  $FC_{\text{non-har}}(t)$  and  $FC_{\text{har}}$  are the cumulative forest carbon stocks of the nonharvest and harvest scenarios in year  $t$ , respectively; and  $C_{\text{inuse}}(t)$  and  $C_{\text{landfill}}(t)$ , respectively, represent the cumulative carbon stocks of in-use wood products and wood products in landfills in year  $t$ , estimated using methods described in Section 5 of the Supporting Information. The sum of the last three items on the right-hand side of the equation represents the total biogenic carbon stocks of the harvest scenario in year  $t$ . So  $C_{FS}(t)$  is the forestry sector biogenic carbon difference between the nonharvest and harvest scenarios in year  $t$ , with positive results representing cumulative biogenic carbon emissions by year  $t$  due to harvest and WBP production, and vice versa.

The cumulative results were converted into annual inventory of emissions/removals by subtracting the carbon stocks of year  $t - 1$  from that of year  $t$ . Production emissions (CO<sub>2</sub> and CH<sub>4</sub> emissions from producing WBP and additive materials; Supporting Information, Section 3) are additional to the forest-atmosphere carbon cycle, and thus were considered in the inventory. To avoid double-counting, the biogenic CO<sub>2</sub> emissions should not

be considered separately. However, CH<sub>4</sub> emissions from decomposition of WBP in landfills need to be included due to their greater climate warming effects relative to CO<sub>2</sub>.

## 2.3 | Wood product substitution effects

Wood product substitution is an important factor affecting forestry sector's climate warming effects. Geng et al. (2019) estimated that construction and furniture manufacturing sectors consumed 61.0% and 28.2%, respectively, of all solid wood products in China between 2004 and 2014, and 64.5% and 24.0% of the wood products consumed by these two sectors, respectively, were substituted for nonwood materials (steel, concrete, brick, plastics, etc.) (Table S5 in Geng et al., 2019). Emission reduction factor, 2.90 tonnes carbon of reduced emissions per tonne carbon contained in wood products used for substitution, was estimated as the reduced emission by increasing wood use to replace alternative materials in wood-intensive scenarios relative to business-as-usual material consumption scenarios in construction and furniture manufacturing industries in China (Geng et al., 2019). We used these factors to estimate the reduced GHG emissions by substituting nonwood materials with WBP in these two sectors in China.

## 2.4 | Characterization method

Carbon dioxide and CH<sub>4</sub> have different lifespans and different atmospheric trapping capacities. These differences need to be considered for estimating forestry sector GHG effects and the consequent climate warming contribution.

### 2.4.1 | Global warming potential

Static LCA has been the dominant method used to assess forestry sector GHG effects. The GWP used to convert non-CO<sub>2</sub> emissions to CO<sub>2</sub>-eq is defined by comparing the heat absorbed by a non-CO<sub>2</sub> GHG in the atmosphere to that of the same mass of CO<sub>2</sub> emissions over a fixed period (often 100 years, i.e., GWP100) (Equation S8). For CH<sub>4</sub>, the GWP100 equals 28 (IPCC, 2014), which reflects the average annual climate warming effects of CH<sub>4</sub> over the 100 years relative to CO<sub>2</sub>. In sLCA, the biogenic carbon balance (Equation 1) is combined with the CO<sub>2</sub>-eq of CH<sub>4</sub> emissions, the fossil fuel-based CO<sub>2</sub> emissions, and wood substitution effects to represent the forestry sector total GHG effects (referred to as "static GHG effects"). And the static carbon neutrality is achieved when the sum of all annual emission components equals the sum of all annual removal components.

### 2.4.2 | Dynamic characterization factor

In the Fifth Assessment Report (IPCC, 2014), the IPCC recommended alternative climate metrics to replace GWP. Based on a critical systematic review, Levasseur et al. (2016) analyzed advances in climate change metrics development in the cause-effect chain from emissions to change of climate. To assess the global warming effects of increased and reduced emissions, Levasseur et al. (2010) developed a radiative forcing-based metric, referred to as the dynamic characterization factor (DCF), based on the same equations and parameters used by IPCC (2014) and measured as watts of heat energy trapped per square meter of the Earth's surface (W m<sup>-2</sup>) (see Section 6 in the Supporting Information). The GHG-specific DCFs for CO<sub>2</sub> and CH<sub>4</sub> (Table S10) represent the instantaneous radiative forcing effects for a 1 kg pulse emission that decline over time (IPCC, 2014; Levasseur et al., 2010), reflecting decay of the two atmospheric GHGs.

Coupled with the temporally explicit life cycle inventory of GHG emissions and removals, the DCFs can be used to estimate the annual global warming effects (W m<sup>-2</sup> yr<sup>-1</sup>) in a given year for all GHG emissions released between year 0 and the given year  $t$  (Equation 2):

$$GWI_{yr}(t) = \sum_i \sum_{j=0}^t g_i(j) \times DCF_i(t-j) \quad (2)$$

in which  $GWI_{yr}(t)$  is the annual global warming effects in year  $t$ , defined as the radiative forcing in year  $t$  caused by the portion of all GHG emissions released from year 0 to year  $t$  that remain in the atmosphere,  $g_i(j)$  denotes the emission or removal of GHG  $i$  in year  $j$ , and  $DCF_i(t-j)$  is the DCF of  $g_i(j)$  in year  $t$  after considering the decay of the GHG in the atmosphere, and  $(t-j)$  denotes the time interval between year  $t$  and the emission year  $j$ .

Note a pulse emission and the same amount of one-time removal (or reduced emission) cancel each other out, resulting in no emissions to the atmosphere and thus no climate effects.

All current life cycle inventory assessment methods use GWP to include non-CO<sub>2</sub> GHGs in the environmental impact analysis for all product systems (Levasseur et al., 2016). Also, cumulative total emissions or removals assessed using sLCA (Section 2.4.1) are widely applied to indicate the forestry sector's effects on atmospheric GHG concentrations. To make the dLCA results comparable to those of sLCA, we formulated Equation (3) to estimate the "dynamic GHG effects" in year  $t$ , based on the annual radiative forcing calculated using Equation (2), which resulted from all GHG emissions released from year 0 to year  $t$  that remain in the atmosphere in year  $t$ :

$$\text{GHG}_{\text{CO}_2\text{-eq}}(t) = \frac{\text{GWI}_{\text{yr}}(t)}{\int_0^1 \alpha_{\text{CO}_2} \times C(t)_{\text{CO}_2} dt} \quad (3)$$

where  $\text{GHG}_{\text{CO}_2\text{-eq}}(t)$  is the dynamic GHG effects that reflects the cumulative GHG emissions/removals (CO<sub>2</sub>-eq) in year  $t$ ; and the denominator on the right-hand side is the radiative forcing caused by 1 kg of CO<sub>2</sub> in the emission year, a constant value. So, the annual radiative forcing and the dynamic GHG effects have the same trends.

Different from static GHG effects that are a simple running total of the emissions and removals, dynamic GHG effects are calculated by considering the timing of emissions and removals and their atmospheric dynamics, representing forestry sector's contribution to increased or decreased atmospheric GHG in year  $t$ . When the annual global warming effects in Equation (2) or the dynamic GHG effects in Equation (3) decrease to zero, total emissions to the atmosphere are completely offset by removal components (carbon sequestration in regenerating forests and decay of CO<sub>2</sub> and CH<sub>4</sub> in the atmosphere, with and without wood substitution considered depending on analysis scenario), a state we refer to as "dynamic carbon neutrality" to distinguish it from static carbon neutrality.

The cumulative global warming contribution in year  $t$  caused by all GHG emissions and removals occurring from year 0 to the given year  $t$ ,  $\text{GWI}_{\text{cum}}$ , is calculated as the sum of the annual global warming effects in the period (Equation 4):

$$\text{GWI}_{\text{cum}}(t) = \sum_{j=0}^t \text{GWI}_{\text{yr}}(j) \quad (4)$$

Climate neutrality is achieved when the cumulative climate effects calculated using Equation (4) decrease to zero, that is, the increases in radiative forcing caused by all the emission components are fully offset by the reduced radiative forcing contributed by removal components (carbon stock recovery in regenerating forest and wood substitution).

## 2.5 | Sensitivity analysis of wood substitution effects

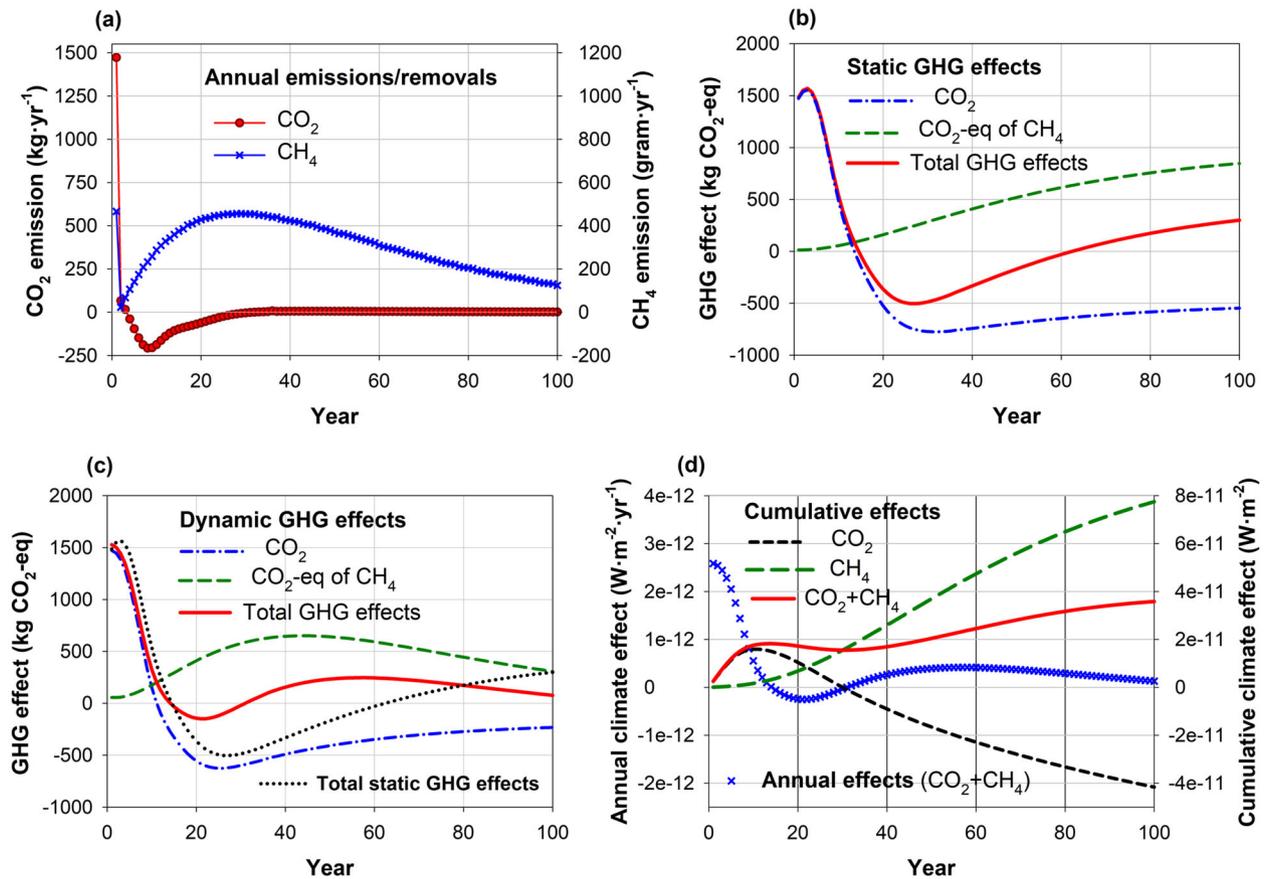
Uncertainties likely exist in the parameters and assumptions used to estimate the reduced emissions from wood substitution. Similar to Harmon (2019), we tested the sensitivity of the GHG and climate effects of the 1990–2018 analysis to these key factors using the following five scenarios: (1) Baseline: All the parameter values described in Section 2.3 were used to estimate substitution effects; (2) reduce substitution: The fractions of wood products used to substitute for nonwood materials, 64.5% and 24.0% in construction and furniture production, respectively, were each reduced by 10% (this scenario is equivalent to reducing the emission reduction factor by 10%, so was used to represent both situations); (3) consider leakage: We assumed 10% of the substitution benefits in the baseline were lost due to cross-sector or cross-jurisdiction leakage; (4) reduce longevity: The emission reduction factor was reduced by 1% each year, assuming a decreasing fossil fuel-dominant future energy system and thus decreasing substitution benefits overtime; and (5) combine changes: The changes in (2)–(4) were combined to estimate the consequent changes in substitution benefits. This is a method to rank sensitivity by changing one factor at a time by a given percentage and assess the changes in substitution effects (Hamby, 1994). Note: Scenario (3) is equivalent to scenario (2) in terms of the dynamic GHG effects and cumulative climate effects but we kept them separate as leakage is a topic of interest (Harmon, 2019). With the use of the primary parameter values, the "baseline" is the best-case scenario in estimating substitution benefits, while the "combine changes" may be considered as the worst scenario.

## 3 | RESULTS

### 3.1 | Global warming effects of 1-m<sup>3</sup> plywood

The dLCA results for the 1-m<sup>3</sup> plywood over a 100-year period are presented in Figure 2 (substitution not included) as (a) inventory of annual emissions and removals, (b) and (c) sLCA and dynamic GHG effects, and (d) annual and cumulative climate effects.

The largest annual emission appeared in year 1 (Figure 2a), including 1266.2 kg biogenic CO<sub>2</sub> and 206.0 kg CO<sub>2</sub> and 466.3 g of CH<sub>4</sub> from energy consumption. In the first 3 years, the carbon sequestration in regenerating forest under the harvest scenario was less than that under the nonharvest



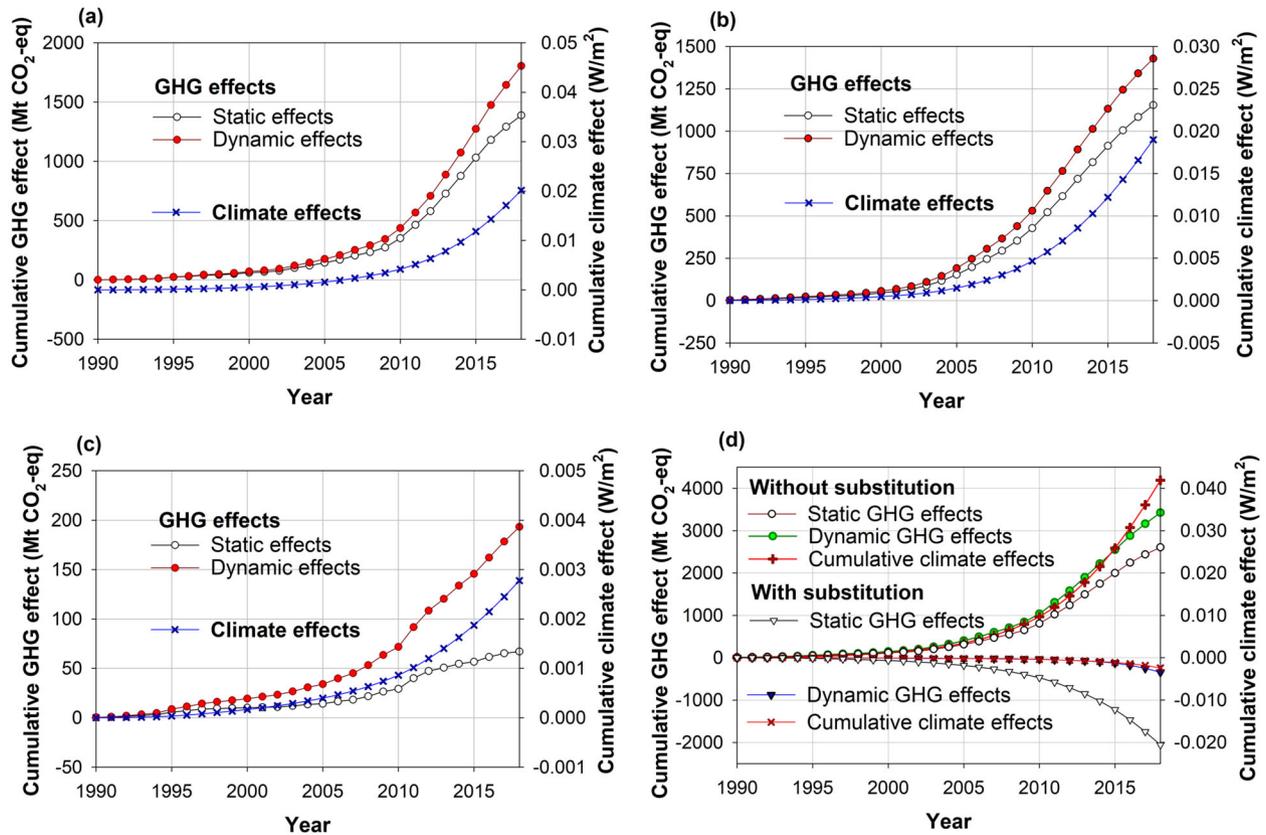
**FIGURE 2** Emissions and removals and the consequent climate effects of 1 m<sup>3</sup> of plywood (substitution not considered): (a) annual emission and removal inventory of carbon dioxide (CO<sub>2</sub>) (left Y-axis) and methane (CH<sub>4</sub>) (right Y-axis) emissions, (b) static greenhouse gas (GHG) effects estimated using static life cycle assessment (sLCA), in which CH<sub>4</sub> was converted to CO<sub>2</sub>-equivalent (CO<sub>2</sub>-eq) using its 100-year global warming potential (28), (c) dynamic GHG effects estimated using dynamic life cycle assessment (dLCA); static GHG effects were also displayed to illustrate the difference between static and dynamic GHG effects, and (d) annual (left Y-axis) and cumulative climate effects (right Y-axis) of the CO<sub>2</sub> and CH<sub>4</sub> emissions. Positive and negative values in (a) and (b) represent increased and reduced GHG emissions, respectively, positive and negative values in (c) indicate the increased and reduced GHG in the atmosphere, respectively, and positive and negative values in (d) respectively suggest increased and reduced radiative forcing. Underlying data for this figure is available in Table S12 in Section 8 of the Supporting Information

scenario, causing additional biogenic CO<sub>2</sub> emissions. From year 4 to year 33, the biogenic carbon balances (Equation 1) were annual sinks, but after year 34 changed to small annual emissions again. Landfill CH<sub>4</sub> emissions increased from year 2 to a peak of 456.6 g in year 28 (Figure 2a) and then decreased.

In the sLCA (Figure 2b), cumulative CO<sub>2</sub> emissions decreased to zero by year 13.5, and then remained as net removals with a peak of 775.1 kg CO<sub>2</sub> in year 32. Cumulative CH<sub>4</sub> emissions increased from year 1 to 847.4 kg CO<sub>2</sub>-eq by year 100. The running total of CO<sub>2</sub> and CH<sub>4</sub> (solid red curve) shows that static carbon neutrality was achieved by year 14.5, with a peak removal of 503.7 kg CO<sub>2</sub>-eq by year 27. The cumulative results became net emissions again after year 62.4, and by year 100, the 1-m<sup>3</sup> plywood resulted in a total of 300.5 kg CO<sub>2</sub>-eq net emission to the atmosphere.

In the dLCA (Figure 2c), the initial increases in atmospheric CO<sub>2</sub> decreased to zero by year 11.1, caused by atmospheric decay and carbon re-sequestration in regenerating forest that reduced atmospheric CO<sub>2</sub> the most by year 25. The CH<sub>4</sub> component in the atmosphere reached a peak of 651.4 kg CO<sub>2</sub>-eq in year 45, and then decreased to 308.7 kg CO<sub>2</sub>-eq by year 100, determined by the balance of annual inputs and decay of the GHG in the atmosphere. The combined CO<sub>2</sub> and CH<sub>4</sub> results show that before year 14.2 and after year 31, the 1-m<sup>3</sup> product increased atmospheric GHG, while between these years, it reduced GHG in the atmosphere.

As expected, annual climate effects (Figure 2d) trends were the same as those for dynamic GHG effects (Figure 2c). Cumulative climate warming contribution from CH<sub>4</sub> increased steadily, while the initial CO<sub>2</sub> emissions contributed to initially increased warming, which gradually changed to CO<sub>2</sub> removals and reduced climate warming. Overall, the production and use of the 1-m<sup>3</sup> plywood caused  $3.59 \times 10^{-11}$  W m<sup>-2</sup> of increased radiative forcing (solid red curve).



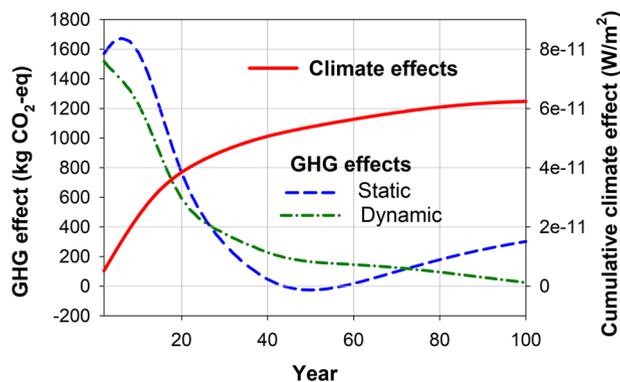
**FIGURE 3** Greenhouse gas (GHG) effects and global warming contribution of the wood-based panels produced from 1990 to 2018 in China, estimated using business-as-usual parameters/assumptions (note: in (a)–(c), substitution effects were not included; GHG effects and climate effects are measured using left and right Y-axes, respectively): (a) plywood, (b) fiberboard, (c) particleboard, and (d) static and dynamic GHG effects and cumulative climate warming contribution of the three products (with and without substitution). Underlying data for this figure is available in Table S13 in Section 8 of the Supporting Information

The total static and dynamic GHG effects were similar before year 14, but very different afterward (Figure 2c): Between year 14 and 80, the static effects were much larger carbon sinks for a much longer period and smaller carbon sources in a much shorter period; after year 80, the static GHG effects continued to increase and became larger sources than the dynamic GHG effects, which decreased. The results suggest that using sLCA largely overestimated the GHG mitigation or underestimated the mitigation contribution in the short- to medium-term relative to dLCA. Note that the static and dynamic carbon balance differed from the climate effects, suggesting the need to assess climate effects for forestry mitigation activities.

### 3.2 | Climate effects of China's wood-based panel forestry sector, 1990–2018

Annual production of WBP in China increased dramatically (Table S1). In the 29 years, plywood accounted for 59.7% of the total WBP production in China, followed by fiberboard (28.9%) and particleboard (11.4%).

Our results show that using sLCA the contributions of China-made WBP to atmospheric GHG concentrations were greatly underestimated relative to using dLCA (Figure 3). When substitution was not considered, the production and use of plywood, fiberboard, and particleboard from 1990 to 2018 in China released 1388.5, 1154.2, and 66.9 Mt CO<sub>2</sub>-eq net emissions to the atmosphere, respectively (Figure 3a–c), or 2609.7 Mt CO<sub>2</sub>-eq in total (Figure 3d). In comparison, using dLCA, these products resulted in increased atmospheric GHG of 1805.2, 1428.9, and 193.2 Mt CO<sub>2</sub>-eq by 2018, respectively (Figure 3a–c), or a total of 3427.3 Mt CO<sub>2</sub>-eq, and contributed  $4.19 \times 10^{-2}$  W m<sup>-2</sup> of increased radiative forcing (Figure 3d). When substitution was considered, static carbon neutrality was achieved immediately in 1990 for the three products combined, with a total of 2059.4 Mt CO<sub>2</sub>-eq of GHG removed from the atmosphere by 2018; with dLCA, these products resulted in 0.5 Mt CO<sub>2</sub>-eq more GHG in the atmosphere in 1990, but dynamic carbon neutrality was achieved by 1995; in total, these products resulted in 342.1 Mt CO<sub>2</sub>-eq less GHG in the atmosphere by 2018, cumulatively contributing  $2.42 \times 10^{-3}$  W m<sup>-2</sup> of reduced radiative forcing.



**FIGURE 4** Static and dynamic greenhouse gas (GHG) effects (kg carbon dioxide-equivalent, kg CO<sub>2</sub>-eq; measured using left Y-axis) and cumulative climate warming effects (watts of heat energy trapped per square meter of the Earth's surface, W m<sup>-2</sup>; measured using right Y-axis); estimated using static and dynamic life cycle assessment for 1 m<sup>3</sup> of plywood by extending the rotation period to 26 years while assuming slower forest growth. Underlying data for this figure is available in Table S14 in Section 8 of the Supporting Information

## 4 | DISCUSSION

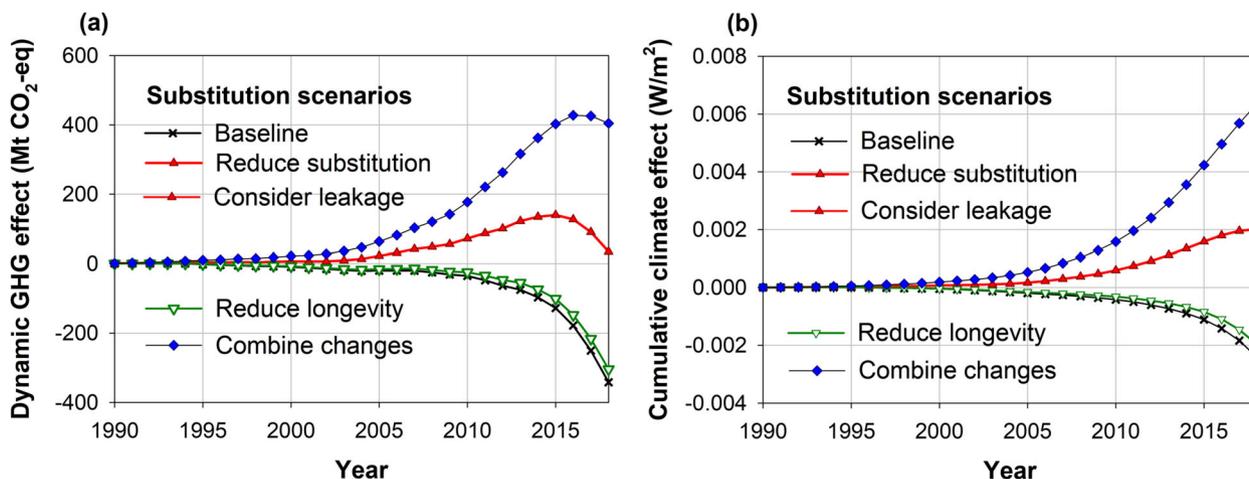
Considering the atmospheric decay of GHG emissions differentiates dLCA from sLCA (Figure 2b,c). For example, 1 unit mass of CH<sub>4</sub> can trap 120 times the heat of the same mass unit of CO<sub>2</sub> in the emission year (equivalent to a GWP of 120), as reflected by the DCFs (Table S10); however, due to atmospheric decay of CH<sub>4</sub>, these warming effects decrease to 59.1, 27.4, 3.8, and 1.3 times in year 10, 20, 50, and 100, respectively, or an average of 28 over 100 years (i.e., the GWP100 of CH<sub>4</sub>). So, the use of a single GWP100 is only accurate for assessing the global warming contribution for a pulse CH<sub>4</sub> emission over a 100-year period. Similarly, 71.0% and 42.5% of a pulse CO<sub>2</sub> emission remains in the atmosphere 10 and 100 years later, respectively. Furthermore, it is normal to have variable annual emissions and removals from the forestry sector (Figure 2a). So the use of a single GWP for CH<sub>4</sub> and the simple running total of all emissions and removals in sLCA can result in underestimated climate warming contribution (or overestimated warming reduction) in the short term, and overestimated climate warming effects (or underestimated contribution to reduced warming) in the long term.

In the 29-year analysis (Figure 3d), when substitution was not included, the static GHG effects suggested total emission to the atmosphere of 2609.7 Mt CO<sub>2</sub>-eq by 2018; however, the dynamic GHG effects suggested that atmospheric GHG increased by 3427.3 Mt CO<sub>2</sub>-eq by 2018, which increased radiative forcing more than indicated by the static GHG effects. In contrast, when substitution was included, in dLCA, carbon neutrality was achieved in year 1995 with atmospheric GHG reduced by 342.1 Mt CO<sub>2</sub>-eq by 2018, compared to 2059.4 Mt CO<sub>2</sub>-eq removals in sLCA with carbon neutrality achieved immediately in year 1990. So sLCA results likely imply much greater contribution to climate warming mitigation than is represented by the dynamic GHG effects.

Essential mitigation goals and timelines were set in the 2015 Paris Agreement for controlling temperature rise in this century. In the 1-m<sup>3</sup> plywood analysis, static and dynamic carbon neutrality were achieved in 14 years or so, but the product resulted in increased cumulative climate warming over the entire 100 years. To assess the climate effects of forestry activities, which often have a decades or longer time lag between emissions and removals, it is essential to use dLCA to estimate the time required to achieve carbon and climate neutrality and assess climate effects within a given timeframe.

Similar results can be found in or derived from a few recent wood product LCA studies. Levasseur et al. (2012) conducted a wood chair case study with a 50-year service life; the results suggested dynamic carbon neutrality was achieved at around year 40, while climate neutrality was achieved between year 75 and 280, depending on the end-of-life scenarios. Demertzi et al. (2018) estimated the carbon footprint of cork produced from harvesting oak forests in Portugal: within a 20-year time horizon, Portugal's cork sector was estimated to be a 62,570 kg CO<sub>2</sub>-eq net removal based on sLCA, which increased to 65,570 kg CO<sub>2</sub>-eq by year 100; in comparison, using dLCA, it was estimated to represent a net removal of 8027 kg CO<sub>2</sub>-eq by year 20 and 91,609 kg CO<sub>2</sub>-eq in 100 years. This result matches findings from the present study that, in the short term, using sLCA largely overestimated the reduced emissions relative to dLCA, while over a longer term using sLCA underestimated emissions reduction. Product types and their end uses are important. In a Swedish case study, Peñaloza et al. (2019) found that if the harvested wood was used to produce biofuel to replace fossil fuels, it needed about 70 years to achieve carbon neutrality but if the wood was used to produce cross-laminate panels to substitute for concrete in buildings, carbon and climate neutrality were achieved from year 1.

The short rotation period of the poplar plantation considered in this study was a main factor resulting in the short carbon neutral time. To show this, we conducted an additional 1-m<sup>3</sup> plywood assessment by increasing the rotation period to 26 years and assuming slower forest growth. In this scenario, the static carbon neutral time increased to 43.7 years (Figure 4), while dynamic carbon neutrality time changed to likely shortly after



**FIGURE 5** Sensitivity analysis of dynamic greenhouse gas (GHG) effects and cumulative climate warming contribution based on changes in substitution assumptions: (1) Baseline—basic assumptions used in the study; (2) reduce substitution—reducing the wood-based panels used to substitute for nonwood materials by 10%; (3) consider leakage—assuming 10% of reduced emissions were released elsewhere; (4) reduce longevity—assuming the emission reduction factor decreased by 1% each year; and (5) combine changes—including all changes in (2)–(4). Underlying data for this figure is available in Table S15 in Section 8 of the Supporting Information. Note: In terms of GHG and climate effects, scenario (2) and (3) are equivalent and were reported using the same symbol and line

year 100. Consequently, the climate warming contribution increased from  $3.59 \times 10^{-11} \text{ W m}^{-2}$  (Figure 2d) to  $6.24 \times 10^{-11} \text{ W m}^{-2}$ , suggesting a much longer time to achieve climate neutrality, if achievable. This result was also documented in previous studies, for example, we derived long carbon and climate neutral time from Levasseur et al. (2012) and Peñaloza et al. (2019), as summarized earlier.

Estimated based on a few key factors, the substitution benefits of reduced emissions were a major component in determining the GHG and climate effects (Figure 3d). Using the five scenarios defined in Section 2.5, we analyzed the sensitivity of the dynamic GHG effects and climate warming contribution for the three WBP produced in China from 1990 to 2018 (Figure 5). In the “baseline” scenario, the WBP became carbon and climate neutral in 5.3 and 6.4 years, respectively, and contributed 342.1 Mt CO<sub>2</sub>-eq of reduced atmospheric GHG and  $2.42 \times 10^{-3} \text{ W m}^{-2}$  of reduced radiative forcing by 2018. In the “reduce substitution” scenario, dynamic carbon neutrality was not achieved in the 29 years, and the products contributed to 34.9 Mt CO<sub>2</sub>-eq of increased GHG and  $2.02 \times 10^{-3} \text{ W m}^{-2}$  increased radiative forcing by 2018. The “consider leakage” scenario was equivalent to scenario (2) in changing the GHG and climate effects. For the “reduce longevity” scenario, it took 5.5 and 7.0 years to achieve carbon and climate neutrality, while contributing to 304.4 Mt CO<sub>2</sub>-eq of reduced atmospheric GHG and  $1.97 \times 10^{-3} \text{ W m}^{-2}$  reduced radiative forcing by 2018. Not surprisingly, the “combine changes” scenario increased atmospheric GHG (404.6 Mt CO<sub>2</sub>-eq) and radiative forcing ( $6.36 \times 10^{-3} \text{ W m}^{-2}$ ) the most in the 29 years. The results indicated the emission reduction factor and the fractions of WBP used in substitution are the most important parameters in determining the substitution benefits, and therefore the dynamic GHG effects and climate warming contribution for China-made WBP. Thus, reducing uncertainty in these parameters is important to improve estimates of substitution effects.

Energy consumption for producing WBP in China was one of the largest sources of production emissions, due in part to fossil fuel-intensive heat and electricity generation in China (Table S2), and resulting in a generally more GHG-intensive WBP industry relative to other major producers in the world (Table S11). The use of chemical additives in manufacturing WBP in China appeared to be the second largest source of production emissions (Table S2). For example, producing 1-m<sup>3</sup> fiberboard uses 110.0 kg of urea formaldehyde in China compared with 44.4 kg in Spain (Rivela et al., 2006, 2007). Thus, reducing energy consumption and the amount of chemical additives are valid options to reduce production emissions for WBP made in China.

Among the three products, manufacturing plywood requires more logs but less energy and additional materials, while the longer average service life the product has indicates longer carbon storage and later end-of-life emissions and thus less radiative forcing accumulated during the study period. Landfill CH<sub>4</sub> emissions appeared to be a decisive factor in determining the long-term GHG effects and climate warming contribution in the 1-m<sup>3</sup> plywood analysis. Since poplar plantations provided almost 60% wood biomass to produce WBP in China, the study results better suited to the 60% WBP. Further investigations should consider other wood biomass sources for all China-made WBP.

Increased wood demand can result in improved forest management and increased forest areas (Cintas et al., 2017; Miner & Gaudreault, 2020). Thus, not considering these economic-driven factors can result in underestimated emission reductions or overestimated emissions increases by the forestry sector. However, including the effects of economic-driven factors or policy incentives may introduce additional uncertainties, and is beyond the scope of the current study.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting information of this article.

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## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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