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ORIGINAL ARTICLE

Full accounting of the greenhouse gas budget in the forestry of China

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Abstract Forest management to increase carbon (C) sinks and reduce C emissions and forest resource utilization to store C and substitute for fossil fuel have been identified as attractive mitigation strategies. However, the greenhouse gas (GHG) budget of carbon pools and sinks in China are not fully understood, and the forestry net C sink must be determined. The objective of this study was to analyze potential forest management mitigation strategies by evaluating the GHG emissions from forest management and resource utilization and clarify the forestry net C sink, and its driving factors in China via constructing C accounting and net mitigation of forestry methodology. The results indicated that the GHG emissions under forest management and resource utilization were 17.7 Tg Ce/year and offset 8.5% of biomass and products C sink and GHG mitigation from substitution effects from 2000 to 2014, resulting in a net C sink of 189.8 Tg Ce/year. Forest resource utilization contributed the most to the national forestry GHG emissions, whereas the main driving factor underlying regional GHG emissions varied. Afforestation dominated the GHG emissions in the southwest and northwest, whereas resource utilization contributed the most to GHG emissions in the north, northeast, east, and south. Furthermore, decreased wood production, improved product use efficiency, and forests developed for bioenergy represented important mitigation strategies and should be targeted implementation in different regions. Our study provided a forestry C accounting in China and

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indicated that simulations of these activities could provide novel insights for mitigation strategies and have implications for forest management in other countries.

Keywords Afforestation · Greenhouse gas emissions · Harvesting and resource utilization · Net carbon sink · Silviculture

1 Introduction

Forest ecosystems are dominant terrestrial ecosystems that play an important role in absorbing atmospheric CO_2 and mitigating global climate change. The expansion of forest areas and the regrowth of forest stands can increase forest biomass carbon (C) (Fang et al. 2014). However, forest C is also strongly modulated by forest management and resource utilization strategies, such as afforestation and silviculture and the harvesting and utilization of forest resources for timber and bioenergy, which alter the composition, structure, and function of forests (Thom and Seidl 2016). Forest management and resource utilization play a dual role in the forestry C budget by increasing or decreasing C stocks in the biomass and products or using firewood as a C-neutral bioenergy substitute for fossil fuels (Timmermann and Dibdiakova 2014). Studies of forest management have shown that afforestation and silviculture could increase the forest area and promote forest growth, thereby increasing the forest biomass C (Zhang and Liang 2014). However, the fossil fuel energy required for the production, transportation, and usage of products in afforestation and silviculture operations releases greenhouse gas (GHG) indirectly and offsets the increases of forest biomass C stocks (Liu et al. 2016a, b). The utilization of forest resources, such as via harvesting, could release GHGs indirectly during the harvesting process or directly via the subsequent decomposition of dead organic matter (DOM) after harvesting, the degradation of wood-based products manufactured from timber, and the combustion of bioenergy (Kilpeläinen et al. 2011). In contrast, substituting forest bioenergy for fossil fuel may contribute to mitigating climate change (Chen et al. 2014). Regarding forest biomass, GHG emissions whether direct or indirect are important to the forestry (Kilpeläinen et al. 2011). Thus, an assessment of forestry as a pathway toward climate mitigation should include the C dynamics of forest growth, forest management, and resource utilization because these processes affect the C budget of forest-atmosphere interactions.

Global forestry has a mitigation potential of 0.2 to 13.8 Pg CO_2e/year by 2030 (Smith et al. 2014), and forest management and forest resource utilization as well as afforestation and reforestation are attractive mitigation options (IPCC 2014; FAO 2016). Many studies have indicated the GHG mitigation potential of forestry from a forest management and resource utilization perspective at both global and regional scales. Lundmark et al. (2014) estimated that forest management, especially intensive silvicultural methods, represented an effective method of reducing C emissions in Sweden and mitigated 10.9 Tg C/year. The Food and Agriculture Organization of the United Nations (FAO) (2016) stated that forest resource utilization contributes to the removal of CO_2 from the atmosphere because of C stored in products and the substitution effect. Xu et al. (2017) demonstrated that improving forest resource utilization would mitigate 114.8 Tg in C emissions in British Columbia from 2017 to 2050. Because of the complexity of considering the C flows within and among forest ecosystems and wood products, and the substitution of fossil fuels with bioenergy, a thorough assessment of the net effect of forestry on climate mitigation is lacking (Xu et al. 2017).

China has established the world's largest government-financed payment for afforestation projects in recent decades, and the forest area has increased by 3 × 10^6 ha/year (FAO 2010). Previous studies have shown that forests in China act as C sinks, and the C sink has increased in 112.9–166.0 Tg C/year since 2000 (Pan et al. 2011; Guo et al. 2013; Zhang et al. 2013). However, the effects of forest management and resource utilization on forest C sinks and the net forestry C sink have not been considered. In addition, the intensity and structure of forest management and resource utilization have changed substantially over the past 15 years. (1) Afforestation and silviculture areas changed from 5.1×10^6 and 25.5×10^6 to 6.0×10^6 and 17.9×10^6 ha, respectively; 67.1% of afforestation occurred in the north, southwest, and northwest while 66.9% of silviculture occurred in the east, south, and northwest. (2) Because of economic development, the demand for and the structure of wood products have changed. For example, wood production increasing by 35.1×10^6 m^3, with 65.1% of the production concentrated in the east and south. Additionally, the proportions of timber and firewood production changed by 90.3–93.1 and 7.0–9.7%, respectively (CMF 2001–2015). All of the abovementioned spatial-temporal variations in forest management and resource utilization may have induced spatial-temporal changes in the GHG emissions, forest C sinks, and C mitigation, which constitute the GHG budget of forestry.

Recent studies have addressed one or a few forest management or resource utilization-induced GHG emissions in China. Liu et al. (2016a, b) reported that afforestation activity-related GHG emissions in the Natural Forest Protection Program and Grain for Green Program totaled 65.85 Tg C from 2000 to 2010, and these emissions could offset the C sequestration obtained by these programs (1159.9 Tg C in total; Fang et al. 2015). Fu et al. (2011) determined that C emissions from harvesting and resource utilization was 34.3 Tg C/year from 1990 to 2009. However, a comprehensive estimation of the GHG budget for forest management and resource utilization is still lacking. In this study, we assessed the spatial-temporal pattern of the GHG emissions from afforestation, silviculture, harvesting, and resource utilization and the net C sink for forestry in China from 2000 to 2014 by constructing the C Accounting and Net Mitigation of Forestry (CANM–Forestry) methodology. The primary objective of this work was to address potential mitigation strategies of forest management by evaluating the GHG budget for forest management and resource utilization, the net C sink effects of China's forestry, and their driving factors over the first 15 years of the twenty-first century.

2 Materials and methods

2.1 Behavior of GHGs under forest management and resource utilization

Afforestation, silviculture, and forest stand regrowth could increase the forest biomass C stock. However, the materials used in afforestation and silviculture activities release GHGs during their production, transportation, and application, thereby offsetting the observed increases in forest C stocks (Fig. 1). Furthermore, during forest stand growth, disasters and harvesting cause a loss of biomass and decrease the C stocks; and forest C stocks reduce the C loss from disasters and harvesting and result in forest biomass C sequestration. During harvesting, the consumption of materials also emits GHGs. After harvesting, approximately 40% of the aboveground biomass is left on-site, and this material can be regarded as DOM and decomposes at 0.1/year (Houghton and Hackler 1999). The remainder is removed from the forest ecosystem as harvested wood products (HWPs) and forms the HWP C stock, which will eventually release CO_2 at various rates. Approximately 20% of the biomass in HWPs decomposes rapidly (1.0/year), 30% is turned into short-lived products and oxidizes at 0.1/year, and the remaining 10% undergoes long-term oxidization at a rate of 0.01/year (Houghton and Hackler 1999; Ge et al. 2008). The HWP C stocks reduce GHG emissions from HWP decomposition and result in HWP C sequestration. Bioenergy combustion

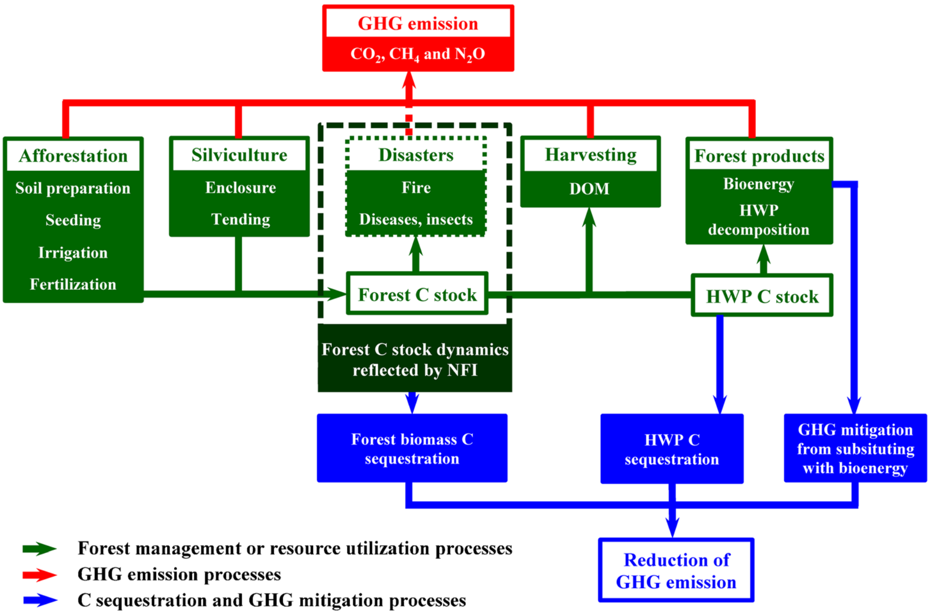

Fig. 1 Behavior of greenhouse gases under forest management and resource utilization (national forest inventory (NFI), which reflected the regrowth of forest stands, the growth of forest stands by afforestation and silviculture, and the biomass loss from disasters and harvesting)

emits GHGs directly, whereas the substitution of fossil fuels with bioenergy could reduce GHG emissions and result in GHG mitigation via the substitution of fossil fuel with bioenergy.

2.2 CANM–Forestry methodology

The CANM–Forestry methodology was used to calculate the GHG emissions from afforestation, silviculture, and harvesting and resource utilization along with the forestry net C sink from 2000 to 2014 in China. The net C sink is equal to the amount of C sequestration and mitigation (including the C sequestered in forest biomass and products, and the C sequestration of mitigation GHG emissions from substitution effects) minus emissions from forestry (including emissions from afforestation, silviculture, harvesting, and resource utilization). This methodology can be summarized as follows: (1) the forestry net C sink was estimated using Eq. 1; (2) GHG emissions from afforestation were obtained by Eqs. 2 and 3; (3) GHG emissions from silviculture were estimated using Eqs. 4 and 5; (4) forest biomass C sequestration was obtained by Eqs. 6 and 7; and (5) GHG budgets for harvesting and resource utilization were estimated using Eqs. 8, 9, 10, 11, 12, 13, 14, and 15. All variables in the methodology are described in Table 1. In the present study, GHGs included CO_2, CH_4, and N_2O, and we converted CH_4 and N_2O into CO_2-C equivalents (Ce) according to their global warming potential (GWP) over 100 years (e.g., $25/44 \times 12 = 6.8$ for CH_4 and $298/44 \times 12 = 81.3$ for N_2O) to facilitate the calculations and discussion (IPCC 2007). We calculated the forestry C budget at the provincial level and indicated the results at the regional level (see Appendix Fig. 3) by summing the provincial results for a specific region.

The CANM–Forestry methodology mainly requires data on the afforestation and silviculture area, the timber and bioenergy production, the forest area, and the timber volume. The main data source is the China Forestry Statistical Yearbook (CMF 1988–2015, 2001–2015), which supplied the data for the afforestation and silviculture area and the timber and bioenergy production for each province. The Chinese Ministry of Forestry publishes the China Forestry Statistical Yearbook with the support of provincial forestry associations. For detailed information on the China Forestry Statistical Yearbook, see Appendix 2. Another source is the Forest Resource Statistics of China (CMF 2005, 2010, 2014), which supplied the data for the forest area and timber volume of different forest types for each province. The Chinese Ministry of Forestry organized the national forest resources inventory and published the Forest Resource Statistics of China. Detailed information on the national forest inventory and the Forest Resource Statistics of China is also provided in Appendix 2. Although the data for our analysis pertained to China, the CANM–Forestry methodology is not specific to China and is generally applicable for the evaluation of GHG budgets for forestry in other countries.

Table 1 Variables used in the Carbon Accounting and Net Mitigation of Forestry (CANM–Forestry) methodology

Variable	Meaning	Units	Equations
NCS	Forestry net C sink	Tg Ce/year	1
EA	GHG emissions from afforestation		1, 2
ES	GHG emissions from silviculture		1, 4
BCS	Biomass C sequestration		1, 6
EH	GHG emissions from harvesting and resource utilization		1, 8
CSH	C sequestration of HWP		1, 14
MFS	Mitigation GHG emissions from substituting fossil fuel with bioenergy		1, 15
EF_{MAj}	GHG emission factor for materials j	t Ce/t	2, 4
MA_{jk}	Amount of material j consumed during afforestation activities k	t/year	2, 3
RMA_{jk}	Amount of material j consumed per area during afforestation activities k	kg/ha	3
AA_k	Implementation area of afforestation activities k	ha/year	3
MS_{jk}	Amount of material j consumed during silviculture activities k	t/year	4, 5
RMS_{jk}	Amount of material j consumed per area for silviculture activities k	kg/ha	5
AS_k	Implementation area of silviculture activities k	ha/year	5
RCS	C sequestration factor via forest growth	kg Ce/ha/year	6, 7
AF	Forest area	ha	6, 7
C_c	Biomass to C content coefficient	Dimensionless	7
S_j	Total area of forest type j	ha	7
V_j	Timber volume per unit area of forest type j	m^3/ha	7
a	Constants of conversion the stand volume to the stand biomass	Dimensionless	7
b			7
EDH	GHG emissions during harvesting process	Tg Ce/year	8, 9
EDA	GHG emissions from the degradation of after-harvested products		8, 10
EBC	GHG emissions from bioenergy combustion		8, 13
EF_{FE}	GHG emission factors from felling	kg Ce/m^3	9
EF_{SK}	GHG emission factors from skidding		9
EF_{LT}	GHG emission factors from log transportation		9
PSK	Proportion of different skidding method	Dimensionless	9
TPV	Timber production	m^3/year	9, 12
k	Decay constant of first-order decay given in units of after-harvested products	/year	10, 11
CS_t	C stock of after-harvested products in year t	Tg Ce	10, 11, 14
IN_t	Inflow to after-harvested products during year t	Tg Ce/year	10, 11, 12
PBA	Proportion of biomass allocated to different after-harvested products	Dimensionless	12
D	Basic density of wood	t/m^3	12, 13
FBC_A	Coefficient of biomass to C content for different after-harvested products	Dimensionless	12
EF_{BC}	GHG emission factor from bioenergy combustion	t Ce/t	13
BPV	Forest bioenergy production	m^3/year	13, 15
EF_{CC}	GHG emission factor from coal combustion	t Ce/tec	15
NCV_c	Net calorific value of coal	tec/t	15

2.2.1 Net forestry C sink

The annual net forestry C sink in province i (NCS_i, Tg Ce/year) is indicated by Eq. 1:

$$NCS_i = -EA_i - ES_i + BCS_i - EH_i + CSH_i + MFS_i \tag{1}$$

where EA_i and ES_i are the GHG emissions from afforestation and silviculture, BCS_i is the forest biomass C sequestration, EH_i is the GHG emissions from harvesting and resource utilization, CSH_i is the C sequestration of HWPs, and MFS_i is the mitigation of GHG emissions via the substitution of fossil fuels with bioenergy.

2.2.2 GHG emissions from afforestation

Equation 2 was used to estimate the GHG emissions from afforestation.

$$EA_i = \sum \left(EF_{MAj} \times MA_{ijk} \right) \times 10^{-6} \tag{2}$$

where EF_{MAj} is the GHG emission factor for material j (i.e., herbicides, fertilizers, water, petrol, and diesel) (t Ce/t) (Appendix 3), and MA_{ijk} is the consumption of material j during afforestation activities k (i.e., soil preparation, seeding, irrigation, and fertilization) in province i (t/year), which can be obtained using Eq. 3.

$$MA_{ijk} = RMA_{ijk} \times AA_{ik} \times 10^{-3} \tag{3}$$

where RMA_{ijk} is the consumption of material j per unit area during afforestation activities k (kg/ha) (Appendix Table 6), and AA_{ik} is the implementation area of the activities k (ha/year).

2.2.3 GHG emissions from silviculture

$$ES_i = \sum \left(EF_{MAj} \times MS_{ijk} \right) \times 10^{-6} \tag{4}$$

where MS_{ijk} is the consumption of material j during silviculture activities k (i.e., enclosure and tending) (t/year), which can be obtained using Eq. 5.

$$MS_{ijk} = RMS_{ijk} \times AS_{ik} \times 10^{-3} \tag{5}$$

where RMS_{ijk} is the consumption of material j per area for silviculture activities k (kg/ha) (Appendix Table 7), and AS_{ik} is the implementation area of the activities k (ha/year).

2.2.4 Forest biomass C sequestration

Volume data were used for the forest stands to reflect the regrowth of the forest stands, the growth of forest stands via afforestation and silviculture, and the biomass loss from disasters and harvesting to estimate BCS_i.

$$BCS_i = RCS_i \times AF_i \times 10^{-9} \tag{6}$$

where RCS_i is the C sequestration factor for forests (kg Ce/ha/year) (Appendix Table 8), which can be obtained using Eq. 7, and AF_i is the forest area (ha).

$$RCS_i = \left[C_C \sum_{i=1}^{31} \sum_{j=1}^{25} S_{ij(k+1)} \left(a_j V_{ij(k+1)} + b_j \right) - C_C \sum_{i=1}^{31} \sum_{j=1}^{25} S_{ijk} \left(a_j V_{ijk} + b_j \right) \right] / (AF_i \times 5) \tag{7}$$

where C_c is the biomass to C content coefficient (equivalent to 0.5) (IPCC 2003); S_{ij} and V_{ij} are the total area (ha) and timber volume per area (m^3/ha) for forest type j (j = 1, 2, 3…, 25) in the k + 1 and k inventory periods; and a_j and b_j are constants for the conversion of volume to biomass for forest type j (Fang et al. 2014). The continuous inventory period is 5 years.

2.2.5 GHG budgets of harvesting and resource utilization

$$EH_i = EDH_i + EDA_i + EBC_i \quad (8)$$

where EDH_i, EDA_i, and EBC_i are the GHG emissions during harvesting, after-harvested product degradation (including DOM and HWP, with the latter including rapid-oxidization products (ROPs), short-lived products (SLPs), and long-term oxidization products (LOPs)), and bioenergy combustion (Tg Ce/year), respectively.

$$EDH_i = \left(EF_{FE} + EF_{SKj} \times PSK_{ij} + EF_{LT}\right) \times TPV_i \times 10^{-9} \quad (9)$$

where EF_{FE}, EF_{SKj}, and EF_{LT} are the GHG emission factors for felling, skidding methods j (i.e., tractor, skyline, and animal), and log transportation (kg Ce/m^3), respectively (Appendix 7); PSK_{ij} is the proportion of methods j (Appendix Table 10); and TPV_i is the timber production (m^3/year).

We used a production approach and counted the GHG emissions from after-harvested products in the timber growth provinces because of the lack of data on the transfer of provincial forest products (Brown et al. 1998). Equation 10 was used to estimate the EDA_i, which reflects the actual conditions of GHG emissions by calculating the gradual decay process.

$$EDA_{i(t+1)} = \sum\left(1-e^{-k_j}\right) \times CS_{ijt} + \sum\left[1-\frac{\left(1-e^{-k_j}\right)}{k_j}\right] \times IN_{ijt} \quad (10)$$

where k is the decay constant of the first-order decay given in units of after-harvested products j (/year) (Appendix Table 11); CS_{ijt} is the C stock of j in year t (Tg Ce); and IN_{ijt} is the inflow to j during year t (Tg Ce/year). CS_{ijt} and IN_{ijt} were estimated using the methods recommended by IPCC (2006).

$$CS_{ijt} = e^{-k_j} \times CS_{ij(t-1)} + \left[\frac{\left(1-e^{-k_j}\right)}{k_j}\right] \times IN_{ij(t-1)} \quad (11)$$

where $CS_{ij(t-1)}$ is the C stock of after-harvested products j at the beginning of year $t-1$, with $CS_{ij(1990)} = 0$ (IPCC 2006). Because of a lack of data on timber production before 1949, using the predictor equation provided by the IPCC (2006) to estimate time production introduces considerable uncertainty, especially because of the dramatic differences in the current population size and level of economic development compared with that in 1949. Thus, we assumed that the C stock of after-harvested products before 1949 was negligible.

$$IN_{ijt} = PBA_j \times D_i \times FBC_{Aij} \times TPV_{it} \times 10^{-6} \quad (12)$$

where PBA_j is the proportion of biomass allocated to after-harvested products j (Appendix Table 11); D_i is the basic density of wood (t/m^3) (Appendix Table 12); FBC_{Aij} is the coefficient of biomass to C content for j (Appendix Table 12); and TPV_{it} is the timber production in year t (m^3/year).

EBC_i can be calculated using Eq. 13.

$$EBC_i = EF_{BC} \times D_i \times BPV_i \times 10^{-6} \quad (13)$$

where EF_{BC} is the GHG emission factor for bioenergy combustion (t Ce/t) (Appendix 11), and BPV_i is the bioenergy production (m^3/year).

CSH_i can be calculated from the C stocks of HWPs by subtracting the GHG emissions from HWP decomposition as follows:

$$CSH_i = CS_i - EDA_i \tag{14}$$

MFS_i can be calculated using Eq. 15:

$$MFS_i = EF_{CC} \times NCV_C \times BPV_i / 2 \times 10^{-6} \tag{15}$$

where EF_{CC} is the GHG emissions factor for coal combustion (t Ce/tec) (Appendix 11); NCV_c is the net calorific value of coal and was equal to 0.71 tec/t (Lu et al. 2010). In this equation, the number 2 denotes that 2 m^3 of bioenergy can be substituted for 1 t of coal in China (Liu et al. 2016a).

3 Results

3.1 Spatial-temporal dynamics of GHG emissions from forest management and resource utilization

The GHG emissions from forest management and resource utilization exhibited substantial spatial-temporal variations (Fig. 2). The national GHG emissions increased dramatically from 12.7 to 25.5 Tg Ce/year during 2000–2014 (Fig. 2g). Of the three factors investigated, afforestation-related GHG emissions (*EA*) increased the most, followed by harvesting and resource utilization-induced GHG emissions (*EH*), whereas silviculture-related GHG emissions (*ES*) decreased by 0.3 Tg Ce. At the regional level, GHG emissions showed an increasing trend, except in the northeast. Most of these increases occurred in the south (4.4 Tg Ce), and 67.2% was contributed by *EH* (Fig. 2d). GHG emissions in the southwest, east, northwest, and north increased by 3.7, 2.7, 1.4, and 0.9 Tg Ce, respectively. Of these increases, 97.5, 56.2, 115.0, and 137.9% were attributed to increases in *EA* (Fig. 2a, c, e, and f), respectively. The GHG emissions in the northeast decreased by 0.4 Tg Ce (Fig. 2b), and 174.2% was attributed to a decrease in *EH*.

From 2000 to 2014, the total GHG emissions from forest management and resource utilization in China was 266.1 Tg Ce (Fig. 2g), and 62.6% of the GHG emissions occurred in the northeast, east, and south. Of the factors investigated, *EH* contributed the most to the national GHG emissions (64.5%), followed by *EA* (34.1%) and *ES* (1.3%). At the regional level, *EH* dominated the GHG emissions in the north, northeast, east, and south, and *EA* presented the largest contribution to the GHG emissions in the southwest and northwest.

3.2 Spatial-temporal variation of the forestry C budget

The spatial-temporal variations in the C sequestration and net C sink values are also shown in Fig. 2. On a national scale, the biomass C sequestration (*BCS*) decreased from 174.9 to 114.2 Tg Ce/year and then increased to 127.6 Tg Ce/year as the afforestation area initially decreased and then increased (Fig. 2g). The HWP C sequestration (*CSH*) increased by 18.8 Tg Ce. In contrast, the GHG emissions also increased gradually with net increases of 35.1 × 10^6 m^3 in wood production and 10.9 × 10^6 t in accumulative fertilization during the study period (CMF 2001–2015). Thus, the net C sink (*NCS*) decreased from 227.3 to 186.8 Tg Ce/year.

Compared with the national trends, the *BCS* behaved in a similar fashion in the north. After subtracting GHG emissions, the *NCS* increased by 5.8 Tg Ce/year (Fig. 2a) and presented an average value of 21.4 Tg Ce/year. The *BCS* also increased by 20.2 and 9.9 Tg Ce/year in the northeast and northwest, which resulted in an increase in the *NCS* by 19.5 and 8.0 Tg Ce/year, respectively (Fig. 2b, f), and the average values were 33.5 and 8.0 Tg Ce/year, respectively. In the east and south, the *BCS* initially increased and then decreased while the *CSH* increased (Fig. 2c, d), which resulted in an increase in the *NCS* of 11.9 and 7.7 Tg Ce/year, and the average values were 33.9 and 35.1 Tg Ce/year. In the southwest, both the *BCS* and *NCS* decreased by 90.6 and 93.3 Tg Ce/year, respectively (Fig. 2e), and the average *NCS* was 57.9 Tg Ce/year. For the six regions, the *NCS* was highest in the southwest and lowest in the northwest.

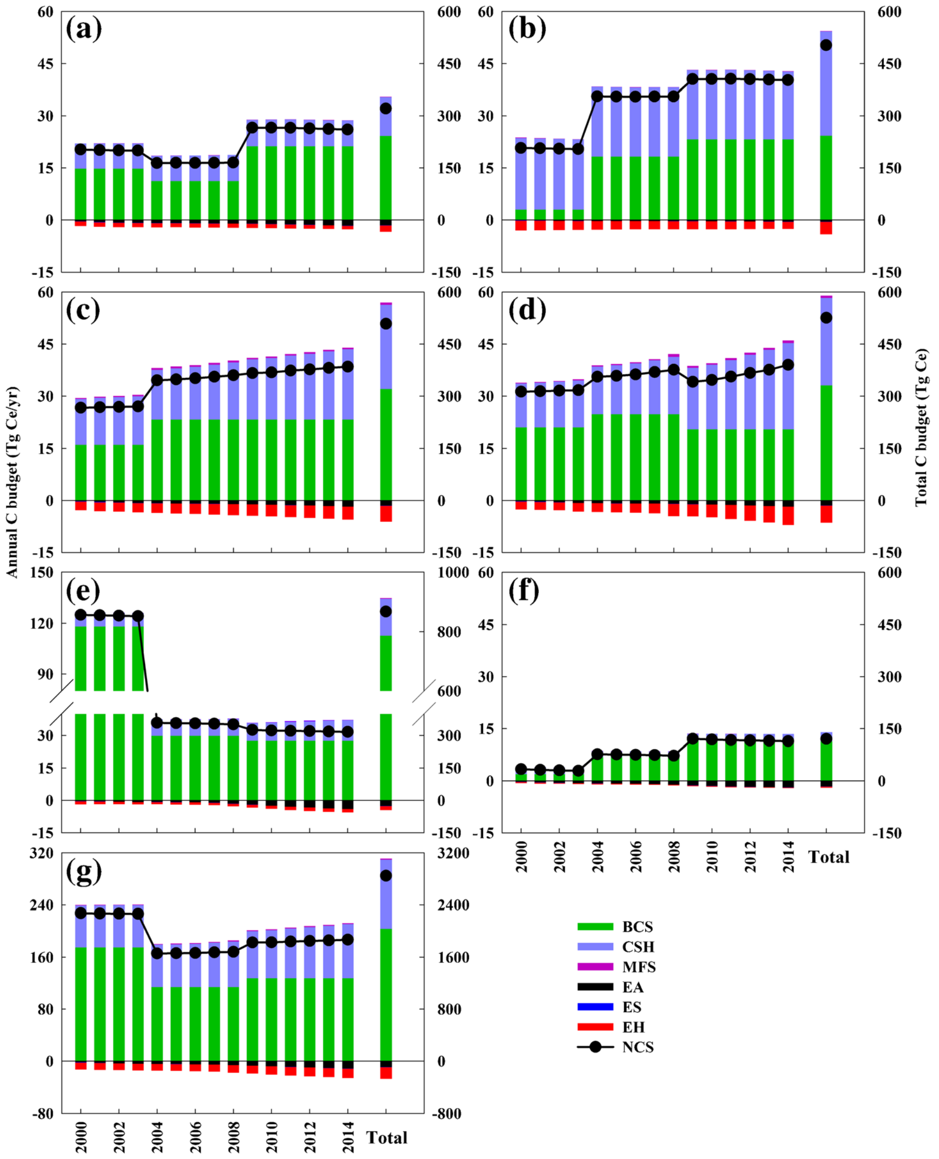

Fig. 2 Spatial-temporal dynamics of the forestry carbon budget in China: **a** north, **b** northeast, **c** east, **d** south, **e** southwest, **f** northwest, and **g** China (*BCS* estimates for 2000–2003, 2004–2008, and 2009–2014 are based on the sixth, seventh, and eighth national forest inventories data, respectively)

3.3 Offset effect of GHG emissions on the C sink

The sum of the *BCS* and *CSH* was 206.3 Tg Ce/year from 2000 to 2014. However, forest management and resource utilization resulted in emissions of 17.7 Tg Ce/year. Moreover, the *MFS* could mitigate 1.3 Tg Ce/year emissions. Therefore, the *NCS* was 189.8 Tg Ce/year. The GHG emissions from forest management and resource utilization offset 8.5% of the biomass and products C sink and GHG mitigation from substitution effects, and the highest offset value was observed in the northwest (Table 2). On a national scale, *EH* offset the greatest amount of the C sink and accounted for 64.5% of the total offset amount. On a regional scale in the north, northeast, east, and south, *EH* was the most important offset of the C sink and accounted for 52.5, 86.8, 74.8, and 76.6% of the regional offsets, respectively. In the southwest and northwest, *EA* offset the greatest amount of the C sink and was responsible for 56.0 and 78.4% of the regional offsets, respectively.

3.4 GHG emissions intensity of forest management and resource utilization

The GHG emissions intensity of forest management and resource utilization showed a spatial pattern because of the spatial heterogeneity of the parameters used to calculate the regional GHG emissions (Table 3). The highest GHG emissions intensity value of afforestation and silviculture occurred in the east and southwest, and the lowest values occurred in the north and east; the highest GHG emissions intensity value of resource utilization occurred in the northwest, and the lowest value occurred in the south.

4 Discussion

4.1 Forestry GHG budgets and net C sink

In our study, the forest biomass C pool in China was 6.5 Pg Ce, whereas the forest biomass C pools in the USA and Europe were 18.9 and 12.4 Pg Ce, respectively (Pan et al. 2011). These differences may be attributable to the smaller forest area and lower C density in China, which are related to the increased level of human disturbance and younger forests. Young forests accounted for 68% of the total forest area in China, whereas they accounted for only 33–37% in the USA and Europe (Oswalt et al. 2014; Vilén 2015). Additionally, the C pool of old-growth forests was 2.2- to 2.3-fold higher than that of young forests (Harmon et al. 1990). However, the biomass C sink in China (135.7 Tg Ce/year) was compared with that in the USA (142.9 Tg Ce/year) and was larger than that in Canada (−57.1 Tg Ce/year) and Japan

Table 2 Offset effects of greenhouse gas emissions on the carbon sink

Region	Offset effects of GHG emissions on the C sink (%)			
	TE/TCS	*EA/TCS*	*ES/TCS*	*EH/TCS*
North	9.6	4.4	0.2	5.0
Northeast	7.6	0.9	0.1	6.6
East	10.8	2.6	0.1	8.1
South	10.8	2.4	0.1	8.3
Southwest	5.0	2.8	0.1	2.1
Northwest	14.2	11.1	0.5	2.6
China	8.5	2.9	0.1	5.5

TE total GHG emissions, *TCS* total C sink

(20.0 Tg Ce/year) (Pan et al. 2011). These differences may be related to the unique age structure of Chinese forests, which are currently in the productive stage (Zhang et al. 2013). Although the C pool in China was relatively smaller than that in the USA and Europe, the data indicate that China's forests have great potential to sequester more C in the future via the development of a larger C sink.

Because of differences in geography, climate, management style, system boundaries, spatiotemporal scales, processes, and methodical assumptions, the GHG emissions from forest management and resource utilization varied considerably in different studies (Liu et al. 2017). In our study, the GHG emissions from forest management and resource utilization (Table 3) were larger than those presented by Kilpeläinen et al. (2011), who estimated that the GHG emissions associated with forest management and resource utilization in Finland were 17.7 and 733.6 kg Ce/ha/year as a result of reduced fossil fuel use or fossil fuel-related product consumption in afforestation, silviculture, and harvesting activities (e.g., fossil fuels consumed by soil preparation in our study and the Kilpeläinen's study were 18 and 15 kg/ha, respectively). Our study also indicated that GHG emissions from forest management and resource utilization offset 8.5% of the biomass and products C sink and GHG mitigation from substitution effects (Table 1), which implies that forest management and resource utilization significantly affects the forestry C budget in China. Excluding GHG emissions, the net forestry C sink was 189.8 Tg Ce/year, which can offset 10.5% of China fossil fuel CO_2 emissions (1810.6 Tg Ce/year during 2000–2014; Boden et al. 2017). However, compared with the global terrestrial C sink of 1900 Tg Ce/year (Le Quéré et al. 2016), the Chinese forestry C sink was smaller and accounted for only 10.0% of the global terrestrial C sink.

4.2 Forest management for GHG mitigation

Forest management is a key strategy for climate change mitigation (Naudts et al. 2016), although its net mitigation effects should deduct GHG emissions from these activities (Liu et al. 2016a, b). Our studies showed that forest management activities emitted 6.3 Tg Ce/year, and 96.2% of this amount was caused by afforestation. However, the C sink generated by afforestation was 81.4 Tg Ce/year based on the reported forest areal expansion, which contributed 60% of the forest biomass C sink (Fang et al. 2014). Therefore, GHG emissions from forest management activities could be compensated for by the C sequestration associated with these activities, indicating that forest

Table 3 Greenhouse gas emission intensity of forest management and resource utilization

Item	GHG emission intensity (kg Ce/ha/year)						
	North	Northeast	East	South	Southwest	Northwest	China
Afforestation	60.9	66.3	121.0	83.5	111.8	74.5	85.6
Soil preparation	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Seeding	0.2	0.3	0.2	0.2	0.2	0.2	0.2
Irrigation	0.3	0.3	0.4	0.2	0.3	0.4	0.3
Fertilization	583.3	872.7	545.4	486.1	332.1	389.7	441.0
Silviculture	1.0	0.9	0.6	0.7	1.6	0.8	0.8
Enclosure	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Tending	0.8	0.9	0.7	0.6	0.5	0.7	0.7
Resource utilization	907.9	1322.8	648.9	433.8	1931.9	2318.8	1005.0
Harvesting process	18.8	18.8	18.4	17.6	17.6	18.8	18.4
After-harvested products	908.1	978.8	714.6	567.3	870.4	1641.1	742.0
Bioenergy combustion	706.5	706.5	849.0	849.0	849.0	849.0	833.6

management represents a feasible mitigation strategy in China. The production and application of fertilizers is one of the most important factors associated with GHG emissions from forestry (González-García et al. 2014). In our study, 98.3% of the afforestation GHG emissions is derived from fertilization because of the N_2O emissions from nitrogen fertilizer applied to economic forests. This is particularly true in the southwest and northwest regions, where large-scale economic forests (e.g., *Eucalyptus* spp., *Hevea brasiliensis*, and *Malus pumila*) distributed. Furthermore, the GHG emissions from fertilization in China (Table 3) were higher than that in the nursery operations in California, which was 360.0 kg Ce/ha/year (Kendall and McPherson 2012), because of the high energy consumption of fertilizer production and the low use efficiency of fertilizer application (Kahrl et al. 2010; Chen et al. 2015). Therefore, improvements to the efficiency of fertilizer production and application could represent a primary mitigation strategy in China and also an important mitigation option for countries that engage in large-scale afforestation, such as India and Vietnam (FAO 2010).

4.3 Utilization of forest resources

The utilization and decomposition of forest resources was responsible for the largest GHG emissions of forestry (Kilpeläinen et al. 2011). Our results also indicated that forest resource utilization accounted for 64.5% of the forestry GHG emissions in China (Fig. 2). The GHG emissions from forest resources in our study were significantly lower than those observed by Fu et al. (2011) because our calculations were based on the gradual decay of GHG emissions from HWP rather than assuming that a portion of HWP is immediately oxidized and releases CO_2 during the harvest year. Forest resource utilization-induced GHG emissions were significantly correlated with wood production ($P < 0.01$**, $n = 465$), indicating that a decrease in wood production is the most important mitigation strategy for the forests of China, particularly in the north, northeast, east, and south. A decrease in wood production might also be an attractive mitigation strategy for countries that suffer from large-scale deforestation, such as the reduction of emissions from deforestation and forest degradation in developing counties (REDD+). Furthermore, the use of forest bioenergy to replace fossil fuels is also a mitigation opportunity. The FAO (2016) indicated that bioenergy could mitigate 109–1200 Tg Ce/year in global emissions. Compared with the global level, the mitigation effect of the substitution of bioenergy for fossil fuel was lower in China, which mitigated only 1.3 Tg Ce/year emissions on a national scale and decreased GHG emissions by 3.6–14.9% in the north, northeast, east, and south regions. This difference may be attributed to only 7.0–9.7% of the wood used as bioenergy in China (CMF 2001–2015), whereas this percentage was approximately 50% for the entire world (FAO 2016). Moreover, the GHG emissions from the substitution of bioenergy for fossil fuel are expected to be recouped by the growth of new forest biomass and result in zero net emissions (Buchholz et al. 2014). Therefore, developing forests for bioenergy should be actively encouraged to mitigate GHG emissions in China, especially in the north, northeast, east and south, and it may also be a promising climate mitigation strategy for Europe, North America, and Oceania, where the percentage of wood used as bioenergy is low (FAO 2010).

4.4 Uncertainties and limitations

Because of a lack of data, we did not consider the GHG budget of the forest soil and the CH_4 and N_2O cycles after harvesting. In the present study, the most important uncertainty is derived from the parameters considered. The CANM–Forestry methodology simulates a wide range of processes and requires many parameters. Based on abundant studies of forests in China, we could collect many observations. However, certain values from technical regulations were different from those produced via practical operations. For instance, technical regulations require that fertilizers be applied using holes; however, in practical operations, forest rangers generally apply fertilizer by root dipping, which reduces the amount of fertilizer. Thus, the GHG emissions generated via fertilization may be overestimated. Future research should address these parametric differences in practical operations.

The second uncertainty is originated from the GHG emission factors. In the present study, the GHG emission factors were mainly caused by the consumption of fossil fuels or fossil fuel-related products (Eqs. 16–31), which were obtained from the IPCC tier 1 level (2006). However, GHG emission factors for fossil fuel consumption may vary with different technologies and equipment from the tier 3 level (IPCC 2006); because we had no data concerning these conditions, they were not considered.

The third uncertainty is generated from biomass C sequestration. Fang et al. (2014) reported that the R^2 values of the biomass expansion factor equations for most forest types were greater than 0.8 and the estimation error should be <3% on a national level. Furthermore, we assumed that the timber volume data from the national forest inventory was able to reflect the volume loss of natural disasters; however, the breakout areas of these disasters from the national forest inventory were different those from forestry-specific inventories (CMF 2001–2015, 2005, 2010, 2014). Therefore, the timber volume from national forest inventory may partly embody the volume loss caused by disasters. If this change was considered, then the forestry net C sink would vary from 182.0 to 189.8 Tg Ce/year.

5 Conclusions

Forest management and resource utilization significantly affect the forestry C dynamics in China. GHG emissions from forest management and resource utilization increased by 12.8 Tg Ce, which was mainly because of increases in afforestation from 2000 to 2014. The total GHG emissions averaged 17.7 Tg Ce/year, and 62.6% was concentrated in the northeast, east, and south; these emissions offset 8.5% of the biomass and products C sink and GHG mitigation from substitution effects, which resulted in a net C sink of 189.8 Tg Ce/year. Forest resource utilization was a major contributor to the national GHG emissions, whereas the key driving factors for regional GHG emissions varied. In the southwest and northwest, afforestation dominated the GHG emissions and was responsible for 56.0 and 78.4% of the C offsets resulting from large-scale economic forests, respectively. In the north, northeast, east, and south, forest resource utilization was the major contributor to GHG emissions because of high wood production, which contributed 52.5–86.8% of the C offsets.

China is the world's largest CO_2 emitter, and forestry play an important role in mitigating these emissions. As forest management, decreased wood production, improved fossil fuels or fossil fuel-related product utilization efficiency and forests developed for bioenergy are important mitigation strategies that could increase the forestry C sink in China and should be targeted for implementation in various regions. These strategies also have important implications and might provide promising mitigation options for forest management in other counties as well. Future research should address the influences of forest management and resource utilization on the forest soil to provide a complete understanding of the role of forestry in climate change mitigation.

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Appendix 1

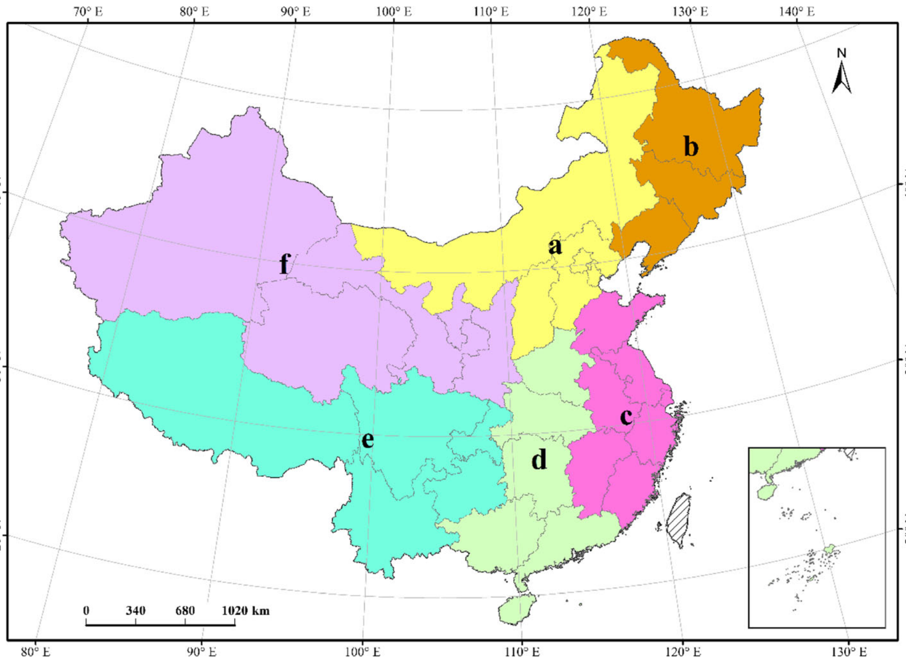

Fig. 3 Forestry regions of China: (a) north (including Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia), (b) northeast (including Liaoning, Jilin, and Heilongjiang), (c) east (including Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, and Shandong), (d) south (including Henan, Hubei, Hunan, Guangdong, Guangxi, and Hainan), (e) southwest (including Chongqing, Sichuan, Guizhou, Yunnan, and Tibet), and (f) northwest (including Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang)

Appendix 2 Detailed information on the data sources

The China Forestry Statistical Yearbook was primarily compiled according to the annual statistical report of forestry for provinces and included forest and wetland resources; ecological construction; industry development; staff and labor remuneration; forestry investments; and six categories of forestry education. The national forest inventory conducted the consecutive inventory of forest resources methodology on a provincial scale. A combination of remote sensing techniques was used to monitor the land use/cover, forest area, volume and distribution, the ecological characteristics, and site conditions of forest stands, which were obtained from 0.41 million permanent sample plots and 2.84 million remotely sensed sample plots compiled in the Forest Resource Statistics of China (CMF 2005, 2010, 2014). The precision of these data was required to be >90% by the sampling design (CMF 2015).

Appendix 3 GHG emission factors for the materials

The GHG emission factor for herbicides ($EF_{Herbicide}$, t Ce/t) was calculated by Eq. 16:

$$EF_{Herbicide} = (E_P + E_{FPT}) \times 0.14 \times 12/44 \tag{16}$$

where EF_P is the energy requirement for herbicide production in MJ/kg active ingredient (ai). This value was 150.9 MJ/kg ai for trifluralin (Audsley et al. 2009). EF_{FPT} is the energy requirement for the formulation, packaging, and transport of an herbicide (assumed as 20 MJ/kg ai) (Green 1987), and 0.14 is a coefficient for converting energy consumption to Ce (kg Ce/MJ) (Chen et al. 2016).

EF_P for 2,4-D butylate was calculated according to Audsley et al. (2009):

$$E_P = -399 + 10.8 \times (Y - 1990) \quad R^2 = 0.57 \tag{17}$$

where Y is the year of the reported discovery of 2,4-D butylate (1942).

The GHG emission factor for petrol combustion (EF_{Potrol}, t Ce/t) was calculated by Eq. 18:

$$EF_{Potrol} = \sum\left(\alpha_k \times NCV_p \times EF_{kp}\right) \times 10^{-9} \tag{18}$$

where α_k is the conversion coefficient for GHG k to GWP (IPCC 2007); NCV_p is the net calorific value for petrol, which was 43,070 kJ/kg (NBS and NDRC 2013); and EF_{kp} is the C emission factor of the GHG k from petrol combustion (kg/TJ) (IPCC 2006).

The GHG emission factor for diesel combustion (EF_{Diesel}, t Ce/t) was calculated by Eq. 19:

$$EF_{Diesel} = \sum(\alpha_k \times NCV_d \times EF_{kd}) \times 10^{-9} \tag{19}$$

where NCV_d is the net calorific value of diesel and equivalent to 42,652 kJ/kg (NBS and NDRC, 2013); and EF_{kd} is the C emission factor of GHG k from diesel combustion (kg/TJ) (IPCC 2006).

The GHG emission factor for synthetic fertilizer ($EF_{Fertilizer}$, t Ce/t) was calculated by Eq. 20:

$$EF_{Fertilizer} = (EF_{NI} + EF_{PH} + EF_{PO}) \times N + EF_{NO2} \times N \times 298 \times 44/28 \times 12/44 \tag{20}$$

where EF_{NI}, EF_{PH}, and EF_{PO} are the integrated GHG emission factors for nitrogen, phosphate, and potash production, and their values are 2.116 t Ce/t N, 0.636 t Ce/t P_2O_5, and 0.180 t Ce/t K_2O, respectively (Chen et al. 2015); N is the proportion of N, P_2O_5, and K_2O in synthetic fertilizer ($N/P_2O_5/K_2O = 1{:}1{:}1$), and the value is 15%; EF_{NO2} is the NO_2 direct emission factor for synthetic fertilizer application (t N_2O-N/t N) (Table 5).

Table 4 Greenhouse gas emission factors for the production or application of different materials

Materials	EF_{MA} (t Ce/t)	Source
Herbicides-2,4-D butylate	2.85	Eqs. 16 and 17
Herbicides-trifluralin	6.53	Eqs. 16 and 17
Petrol	0.85	Eq. 18
Diesel	0.88	Eq. 19
Water	0.02×10^{-3}	Liu et al. 2016a
Iron wire	0.66	Tian et al. 2013; Liu et al. 2016a
Cement	0.19	Wang et al. 2013

Table 5 NO_2 emission factors for synthetic fertilizer applications and greenhouse gas emission factors for synthetic fertilizer applications

Region	EF_{NO2} (t N_2O-N/t N)[a]	$EF_{Fertilizer}$ (t Ce/t)[b]
North	0.00483	0.53
Northeast	0.0101	0.63
East	0.0119	0.67
South	0.0119	0.67
Southwest	0.0119	0.67
Northwest	0.00483	0.53

[a] Zheng et al. (2004)

[b] Our calculation was based on Eq. 20

Appendix 4

Table 6 Material consumption of afforestation activities

Region	Province	*RMA* (kg/ha)						
		SPD[a]	SPH[b]	SDD[c]	SDP[d]	IW[e]	FF[f]	FD[g]
North	Beijing	55.8	5.0	3.7	0.2	460,909.8	21,633.2	257.4
	Tianjin			3.7		321,328.8	17,976.6	213.9
	Hebei			3.7		286,392.2	17,309.7	206.0
	Shanxi			3.7		353,460.0	14,596.7	173.7
	Inner Mongolia			3.9		129,740.5	17,060.8	203.0
Northeast	Liaoning	55.8	5.0	4.8	0.2	304,372.5	17,985.2	214.0
	Jilin					226,069.7	24,121.6	287.1
	Heilongjiang					154,503.7	24,591.1	292.6
East	Shanghai	55.8	5.0	3.3	0.2	485,155.8	13,071.1	155.6
	Jiangsu			3.3		176,504.8	9545.3	113.6
	Zhejiang			3.3		280,474.4	9739.1	115.9
	Anhui			3.3		201,340.2	9555.1	113.7
	Fujian			3.5		115,253.3	8492.9	101.1
	Jiangxi			3.1		122,353.0	6714.5	79.9
	Shandong			3.8		565,183.0	16,010.7	190.5
South	Henan	55.8	5.0	3.8	0.2	319,921.4	14,793.5	176.0
	Hubei			3.1		204,221.8	8840.5	105.2
	Hunan			2.9		103,813.5	6429.4	76.5
	Guangdong			3.5		93,031.4	8520.7	101.4

Table 6 (continued)

Region	Province	*RMA* (kg/ha)						
		SPD[a]	SPH[b]	SDD[c]	SDP[d]	IW[e]	FF[f]	FD[g]
	Guangxi			3.5		188,231.4	11,661.1	138.8
	Hainan			3.6		333,707.1	13,486.7	160.5
Southwest	Chongqing	55.8	5.0	2.9	0.2	121,986.6	6975.5	83.0
	Sichuan			2.9		132,853.6	9311.8	110.8
	Guizhou			2.9		147,205.4	5868.7	69.8
	Yunnan			3.3		377,622.1	7334.6	87.3
	Tibet			5.5		181,336.8	9914.4	112.0
Northwest	Shaanxi	55.8	5.0	3.2	0.2	243,387.8	9605.8	114.3
	Gansu			3.5		268,683.1	12,199.8	145.2
	Qinghai			5.5		78,255.0	8572.5	102.0
	Ningxia			3.5		237,928.4	9441.9	112.4
	Xinjiang			3.4		908,873.9	11,279.8	134.2
China	Total	55.8	5.0	3.5	0.2	41,472.7	10,600.9	126.2

SPD the consumption of diesel for soil preparation, *SPH* the consumption of herbicides for soil preparation, *SDD* the consumption of diesel for seeding, *SDP* the consumption of petrol for seeding, *IW* the consumption of water for irrigation, *FF* the consumption of synthetic fertilizer for fertilization, *FD* the consumption of diesel for fertilization

[a] Our calculation was based on NSPRC (1995), Chen et al. (2008), BMBS and NBSSOB (2011), and Liu et al. (2016a)

[b] Our calculation was based on NSPRC (1995) and Liu et al. (2016a)

[c] Our calculation was based on NSPRC (2006), CMF (2009), and Liu et al. (2016a)

[d] Our calculation was based on NSPRC (2005) and Zhang and Lei (2010)

[e] Our calculation was based on NSPRC (2006) and Zhou and Ao (2014)

[f] Our calculation was based on NSPRC (2006), Zhou and Ao (2014), and Liu et al. (2016a)

[g] Our calculation was based on NSPRC (2006), BMBS and NBSSOB (2011), Zhou and Ao (2014), and Liu et al. (2016a)

Appendix 5

Table 7 Material consumption of silviculture activities

Region	Province	*RMS* (kg/ha)					
		EI[a]	EC[b]	ED[c]	TH[d]	TD[e]	TP[f]
North	Beijing	9.6	362.9	4.4	1.5	3.40	0.6
	Tianjin				1.5		
	Hebei				1.5		
	Shanxi				1.5		
	Inner Mongolia				1.6		
Northeast	Liaoning	9.6	362.9	4.4	2.0	3.41	0.6
	Jilin						
	Heilongjiang						
East	Shanghai	9.6	362.9	4.4	1.3	5.46	6.2
	Jiangsu				1.3		
	Zhejiang				1.3		
	Anhui				1.3		
	Fujian				1.4		
	Jiangxi				1.2		
	Shandong				1.5		

Table 7 (continued)

Region	Province	*RMS* (kg/ha)					
		EI[a]	EC[b]	ED[c]	TH[d]	TD[e]	TP[f]
South	Henan	9.6	362.9	4.4	1.5	0.04	2.8
	Hubei				1.2	0.03	
	Hunan				1.1	0.03	
	Guangdong				1.4	0.03	
	Guangxi				1.4	0.03	
	Hainan				1.4	0.04	
Southwest	Chongqing	9.6	362.9	4.4	1.1	0.03	2.8
	Sichuan				1.1	0.03	
	Guizhou				1.1	0.03	
	Yunnan				1.3	0.03	
	Tibet				2.2	0.05	
Northwest	Shaanxi	9.6	362.9	4.4	1.3	3.39	0.6
	Gansu				1.4	3.40	
	Qinghai				2.2	3.42	
	Ningxia				1.4	3.40	
	Xinjiang				1.4	3.40	
China	Total	9.6	362.9	4.4	1.5	2.54	0.6

EI the consumption of iron wire for enclosure, *EC* the consumption of cement for enclosure, *ED* the consumption of diesel for enclosure, *TH* the consumption of herbicides for forest tending, *TD* the consumption of diesel for forest tending, *TP* the consumption of petrol for forest tending

[a] Our calculation was based on CMF (2009), Shi (2009), and Liu et al. (2016 b)

[b] Our calculation was based on Cao (2004), CMF (2009), and MIITPRC (2010)

[c] Our calculation was based on BMBS and NBSSOB (2011), and Liu et al. (2016a, b)

[d] Our calculation was based on NSPRC (1995, 2006, 2009), and Liu et al. (2016a, b)

[e] Our calculation was based on NSPRC (1995, 2009), Jiang et al. (1995), IPCC 2006), Li and Cai (2006); Xu et al. (2010), BMBS and NBSSOB (2011), and Zhou et al. (2014)

[f] Our calculation was based on Jiang et al. (1995), IPCC (2006), Li and Cai (2006), NSPRC (2009), Xue and Zhang (2009), Xu et al. (2010), Zhou et al. (2014), and Liu et al. (2016a, b)

Appendix 6

Table 8 Carbon sequestration factor for forests

Region	Province	*RCS* (kg Ce/ha/year)[a]		
		2000–2003	2004–2008	2009–2014
North	Beijing	689.1	860.0	1018.3
	Tianjin	−197.1	1096.7	1713.4
	Hebei	173.9	868.4	674.4
	Shanxi	408.0	802.5	1152.8
	Inner Mongolia	845.9	411.7	950.9
Northeast	Liaoning	418.0	840.0	1179.0
	Jilin	378.7	238.1	897.7
	Heilongjiang	−58.5	705.6	608.4
East	Shanghai	1577.4	2064.8	1482.9
	Jiangsu	2855.4	1621.0	1906.8

Table 8 (continued)

Region	Province	*RCS* (kg Ce/ha/year)[a]		
		2000–2003	2004–2008	2009–2014
	Zhejiang	103.9	1140.5	884.0
	Anhui	511.2	1006.6	1059.9
	Fujian	848.8	792.8	1671.4
	Jiangxi	928.8	925.4	301.4
	Shandong	1893.3	2071. 1	1013.8
South	Henan	1616.8	1618.7	1067.0
	Hubei	331.4	1012.2	1157.9
	Hunan	688.8	897.6	−12.5
	Guangdong	791.5	184.8	743.5
	Guangxi	876.0	896.1	450.2
	Hainan	613.3	30.9	1620.9
Southwest	Chongqing	5901.1	1335.8	1284.4
	Sichuan	248.4	640.3	637.3
	Guizhou	1045.7	1548.2	1396.1
	Yunnan	701.0	646.3	621.9
	Tibet	11,034.8	505.8	130.9
Northwest	Shaanxi	60.4	545.2	1203.4
	Gansu	100.9	857.2	894.4
	Qinghai	826.3	712.4	860.5
	Ningxia	−1230.5	757.6	1062.4
	Xinjiang	820.9	923.4	1281.7
China	Total	689.1	860.0	1018.3

[a] Our calculation was based on CMF (2005, 2010, 2014)

Appendix 7 GHG emission factors for the harvesting process

EF_{FE} was calculated by Eq. 21:

$$EF_{FE} = EF_{Petrol} \times DU_{FE} \times 10^{-9} \tag{21}$$

where DU_{FE} is the petrol consumption per unit of timber production for felling, and the value was 0.075 kg/m^3 (Zhou et al. 2014).

The GHG emission factors for tractor skidding (EF_{SKT}, kg Ce/m^3) were calculated as follows:

$$EF_{SKT} = EF_{Diesel} \times DU_{SKT} \times D_{SKT} \times 10^{-9} \tag{27}$$

where DU_{SKT} is the diesel consumption per unit of timber production for tractor skidding, and the value is 0.095 kg/m^3/km (Jiang et al. 1993; Zhou et al. 2014); D_{SKT} is the distance for tractor skidding, and the value is 3 km (Zhou et al. 2014).

The GHG emission factors for skyline skidding (EF_{SKS}, kg Ce/m^3) were calculated as follows:

$$EF_{SKS} = EF_{diesel} \times DU_{SKS} \times D_{SKS} \times 10^{-9} \tag{28}$$

where DU_{SKS} is the diesel consumption per unit of timber production for skyline skidding, and the value is 0.5 kg/m^3/km (Zhou et al. 2014); D_{SKS} is the skyline skidding distance, and the value is 0.35 km (Chen 2011).

We assumed that no GHG emissions occurred for animal skidding (EF_{SKA}).

EF_{LT} was calculated as follows:

$$EF_{LT} = \left(EF_{diesel} \times DU_{LFV} + EF_{petrol} \times DU_{LA}\right) \times 1/2 \times D_L \times 10^{-9} \qquad (29)$$

where DU_{LFV} is the diesel consumption per unit of timber production for log transportation by farm vehicles, and the value is 0.07 kg/m^3/km (Chen 2011); DU_{LA} is the petrol consumption per unit of timber production for log transportation by automobile, and the value is 0.042 kg/m^3/km (Ren et al. 1999; Zhou et al. 2014), and 1/2 is the proportion of different log transportation methods; D_L is the log transportation distance, and the value is 40 km (Zhou et al. 2014).

Table 9 Greenhouse gas emission factors for the harvesting process

Parameter	Emission factors (kg Ce/m^3)
EF_{FE}	0.07
EF_{SKT}	0.25
EF_{SKS}	0.15
EF_{SKA}	0.00
EF_{LT}	1.94

Appendix 8

Table 10 Proportions for different skidding methods

Region	*PSK* (dimensionless)[a]		
	Tractor	Skyline	Animal
North	100%		
Northeast	100%		
East	50%	50%	
South		50%	50%
Southwest		50%	50%
Northwest	100%		

[a] Jiang et al. (1995)

Appendix 9

Table 11 Decay rates and biomass fractions allocated to different after-harvested products

After-harvested products	*k* (/year)[a]	*PBA* (dimensionless)[a]
DOM	0.10	40%
ROP	1.00	20%
SLP	0.10	30%
LOP	0.01	10%

[a] Houghton et al. (1983), Houghton and Hackler (1999), and Ge et al. (2008)

Appendix 10

Table 12 Basic density of wood and coefficient of biomass to carbon content for different after-harvested products

Region	D (t/m^3)[a]	FBC_A (dimensionless)[b]			
		DOM	ROPs	SLPs	LOPs
North	0.40	0.51	0.34	0.44	0.51
Northeast	0.40	0.51	0.34	0.44	0.51
East	0.48	0.50	0.34	0.44	0.50
South	0.48	0.48	0.34	0.44	0.48
Southwest	0.48	0.48	0.34	0.44	0.48
Northwest	0.48	0.50	0.34	0.44	0.50
China	0.46	0.50	0.34	0.44	0.50

[a] RIWI and CAF (1982)

[b] Dias et al. (2007, 2009) and Bai (2010)

Appendix 11 GHG emission factors for bioenergy and coal combustion

$$EF_{BC} = \sum\left(\alpha_k \times EF_{kf}\right) \times 10^{-3} \quad (30)$$

where EF_{kf} is the GHG emission factor for GHG k from bioenergy combustion (g/kg), and the value is 1131.40 for CO_2, 2.20 for CH_4, and 1.07 for N_2O (Wang et al. 2009; Lu et al. 2011). The value of EF_{BC} is 0.41 t Ce/t.

$$EF_{CC} = \sum(\alpha_k \times EF_{kc}) \times 0.029 \times 10^{-3} \quad (31)$$

where EF_{kc} is the GHG emission factor for GHG k from coal combustion (kg/TJ), and the value is 81,548.29 for CO_2, 10 for CH_4, and 1.4 for N_2O (IPCC 1997; Ma et al. 1999). The terajoule to tons of standard coal equivalent coefficient (TJ/tec) is 0.029. The value of EF_{CC} is 0.66 t Ce/tec.

References

Boden TA, Marland G, Andres RJ (2017) Global, regional and national fossil-fuel CO_2 emissions. Available from: http://cdiacornlgov/CO2_Emission/timeseries/national Cited 31 May 2017

Brown S, Lim B, Schlamadinger B (1998) Evaluating approaches for estimating net emissions of carbon dioxide from forest harvesting and wood products. IPCC/OECD/IEA Programme on National Greenhouse Gas Inventories. Dakar

Buchholz T, Prisley S, Marland G et al (2014) Uncertainty in projecting GHG emissions from bioenergy. Nat Clim Chang 4:1045–1047

Chen JX, Colombo SJ, Ter-Mikaelian MT et al (2014) Carbon profile of the managed forest sector in Canada in the 20th century: sink or source? Environ Sci Technol 48:9859–9866

Chen S, Lu F, Wang XK (2015) Estimation of greenhouse gases emission factors for China's nitrogen, phosphate, and potash fertilizers. Acta Ecol Sin 35:6371–6383

CMF (Chinese Ministry of Forestry) (1988-2015) China forestry statistical yearbook 1949-2014. Department of Forest Resource and Management. Chinese Ministry of Forestry, Beijing
CMF (2001-2015) China forestry statistical yearbook 2000–2014. Department of Forest Resource and Management. Chinese Ministry of Forestry, Beijing
CMF (2005) Forest resource statistics of China (1999–2003). Department of Forest Resource and Management, Chinese Ministry of Forestry, Beijing
CMF (2010) Forest resource statistics of China (2004–2008). Department of Forest Resource and Management, Chinese Ministry of Forestry, Beijing
CMF (2014) Forest resource report of China—the 8th national forest resources inventory. Chinese Forestry Publishing House, Beijing
Fang JY, Guo ZD, Hu HF et al (2014) Forest biomass carbon sinks in East Asia, with special reference to the relative contributions of forest expansion and forest growth. Glob Chang Biol 20:2019–2030
Fang JY, Yu GR, Ren XB et al (2015) Carbon sequestration in China's terrestrial ecosystems under climate change. Bull Chinese Acad Sci 30:848–857
FAO (Food and Agriculture Organization of the United Nations) (2010) Global forest resources assessment 2010: main reports. FAO, Rome
FAO (2016) Forestry for a low-carbon future: integrating forests and wood products in climate change strategies. FAO, Rome
Fu C, Fang HJ, Yu GR (2011) Carbon emissions from forest vegetation caused by three major disturbances in China. J Res Ecol 2:202–209
Ge QS, Dai JH, He FN et al (2008) Land use changes and their relations with carbon cycles over the past 300 a in China. Sci China Ser D Earth Sci 51:871–884
González-García S, Moreira MT, Dias AC et al (2014) Cradle-to-gate life cycle assessment of forest operations in Europe: environmental and energy profiles. J Clean Prod 66:188–198
Guo ZD, Hu HF, Li P et al (2013) Spatio-temporal changes in biomass carbon sinks in China's forests from 1977 to 2008. Sci China Life Sci 56:661–671
Harmon ME, Ferrell WK, Franklin JF (1990) Effects on carbon storage of conversion of old-growth forests to young forests. Science 247:699–702
Houghton RA, Hackler JL (1999) Emissions of carbon from forestry and land-use change in tropical Asia. Glob Chang Biol 5:481–492
IPCC (2003) LUCF sector good practice guidance. In: Penman J et al (eds) Good practice guidance for land use, land-use change, and forest. Institute for Global Environmental Strategies (IGES), Kanagawa
IPCC (2006) 2006 IPCC guidelines for national greenhouse gas inventories. IGES, Kanagawa
IPCC (2007) Climate change 2007: the physical science basis. In: Solomon S et al (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
IPCC (2014) Climate change 2014: mitigation of climate change. In: Edenhofer O et al (eds) Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
Kahrl F, Li Y, Su Y et al (2010) Greenhouse gas emissions from nitrogen fertilizer use in China. Environ Sci Pol 13:688–694
Kendall A, Mcpherson EG (2012) A life cycle greenhouse gas inventory of a tree production system. Int J Life Cycle Assess 17:444–452
Kilpeläinen A, Alam A, Strandman H et al (2011) Life cycle assessment tool for estimating net CO_2 exchange of forest production. GCB Bioenergy 3:461–471
Le Quéré C, Andrew RM, Canadell JG et al (2016) Global carbon budget 2016. Earth Syst Sci Data 8:605–649
Liu BJ, Lu F, Wang XK et al (2016a) Greenhouse gas emissions and net carbon sequestration of the Natural Forest Protection Program in China. Acta Ecol Sin 36:4266–4278
Liu BJ, Zhang L, Lu F et al (2016b) Research on greenhouse gas emissions and net carbon sequestration of "Grain for Green" Program in China. Chin J Appl Ecol 27:1693–1707
Liu BJ, Lu F, Wang XK et al (2017) Greenhouse gas emissions, carbon leakage and net carbon sequestration from afforestation and forest management: a review. Chin J Appl Ecol 28:673–688
Lu F, Wang XK, Han B et al (2010) Net mitigation potential of straw return to Chinese cropland: estimation with a full greenhouse gas budget model. Ecol Appl 20:634–647
Lundmark T, Bergh J, Hofer P et al (2014) Potential roles of Swedish forestry in the context of climate change mitigation. Forests 5:557–578
Naudts K, Chen YY, Mcgrath MJ et al (2016) Europe's forest management did not mitigate climate warming. Science 351:597–600

Oswalt SN, Smith WB, Miles PD et al (2014) Forest resources of the United States, 2012: a technical document supporting the foreset service 2015 update of the RPA assessment. Gen tech rep WO-91. US Department of Agriculture, Forest Service, Washington
Pan YD, Birdsey RA, Fang JY et al (2011) A large and persistent carbon sink in the world's forests. Science 333: 988–993
Thom D, Seidl R (2016) Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. Biol Rev 91:760–781
Timmermann V, Dibdiakova J (2014) Greenhouse gas emissions from forestry in East Norway. Int J Life Cycle Assess 19:1593–1606
Vilén T (2015) Effects of changes in land-use, age-structure and management on carbon dynamics of European forests. Dissertation, University of Eastern Finland
Smith P, Bustamante M, Ahammad H et al (2014) Agriculture, forestry and other land use. In: Climate change 2014: mitigation of climate change. In: Edenhofer O et al (eds) Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
Xu Z, Smyth CE, Lemprière TC et al (2017) Climate change mitigation strategies in the forest sector: biophysical impacts and economic implications in British Columbia, Canada. Mitig Adapt Strateg Glob Change. doi:10.1007/s11027-016-9735-7
Zhang CH, Ju WM, Chen JM et al (2013) China's forest biomass carbon sink based on seven inventories from 1973 to 2008. Clim Chang 118:933–948
Zhang YZ, Liang SL (2014) Changes in forest biomass and linkage to climate and forest disturbances over Northeastern China. Glob Chang Biol 20:2596–2606

References in appendix

Audsley E, Stacey KF, Parsons DJ et al (2009) Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use. Cranfield university, Cranfield
Bai YF (2010) Carbon stocks harvested wood products in China. Dissertation, Chinese Academy of Forestry
BMBS (Beijing Municipal Bureau of Statistics), NBSSOB (National Bureau of Statistics Survey Office in Beijing) (2011) Beijing statistical yearbook. China Statistics Press, Beijing
Cao JH (2004) Study on durability of glass fiber reinforced ordinary portland cement. Dissertation, Chongqing University
Chen JS (2011) Study on the influence of plantation operation on resource-environment-economics based on life cycle assessment theory. Dissertation, Nanjing Forestry University
Chen PQ, Wang XK, Wang LM (2008) Carbon budget and its sink promotion of terrestrial ecosystem in China. Science Press, Beijing
Chen S, Lu F, Wang XK (2015) Estimation of greenhouse gases emission factors for China's nitrogen, phosphate, and potash fertilizers. Acta Ecol Sin 35:6371–6383
Chen S, Lu F, Wang XK (2016) Estimation of greenhouse gases emission for pesticides usage in China's major crops. Acta Ecol Sin 36:2560–2569
CMF (2005) Forest resource statistics of China (1999–2003). Department of Forest Resource and Management. Chinese Ministry of Forestry, Beijing
CMF (2009) The estimation indexes of investment in shelterbelt afforestation project. Chinese Forestry Publishing House, Beijing
CMF (2010) Forest resource statistics of China (2004–2008). Department of Forest Resource and Management. Chinese Ministry of Forestry, Beijing
CMF (2014) Forest resource report of China—the 8th national forest sources inventory. Chinese Forestry Publishing House, Beijing
CMF (2015) Forest resources assets assessment technical specification. Standards Press of China, Beijing
Dias AC, Louro M, Arroja L et al (2007) Carbon estimation in harvested wood products using a country-specific method: Portugal as a case study. Environ Sci Pol 10:250–259
Dias AC, Louro M, Arroja L et al (2009) Comparison of methods for estimating carbon in harvested wood products. Biomass Bioenergy 33:213–222
Ge QS, Dai JH, He FN et al (2008b) Land use changes and their relations with carbon cycles over the past 300a in China. Sci China Ser D-Earth Sci 51:871–884
Green MB (1987) Energy in pesticide manufacture, distribution, and use. In: Helsel ZR (ed) Energy in plant nutrition and pest control. Elsevier, Amsterdam
Houghton RA, Hackler JL (1999) Emissions of carbon from forestry and land-use change in tropical Asia. Glob Chang Biol 5:481–492

Houghton RA, Hobbie JE, Melillo JM et al (1983) Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere. Ecol Monogr 53:236–262

IPCC (1997) Energy. In: Allen C et al (eds) Revised 1996 IPCC guidelines for national greenhouse gas inventories. IPCC/OECD/IEA, Paris

IPCC (2006) Energy. In: Eggleston HS et al (eds) 2006 IPCC guidelines for national greenhouse gas inventories. IGES, Hanagawa

IPCC (2007) Climate change 2007: the physical science basis. In: Solomon S et al (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Jiang HX, Sun GX, Zhou GX et al (1993) Skiddding experiment except clear cutting jobs. J Northeast Forestry Univ 21:76–80

Jiang HX, Jiao HS, Jie YL et al (1995) Research and development of skidding. Forest Eng 11:4–7

Li CG, Cai TJ (2006) Effect of forest canopy density on stock volume estimation. J Northeast Forestry Univ 34: 15–17

Liu BJ, Lu F, Wang XK et al (2016a) Greenhouse gas emissions and net carbon sequestration of the Natural Forest Protection Program in China. Acta Ecol Sin 36:4266–4278

Liu BJ, Zhang L, Lu F et al (2016b) Research on greenhouse gas emissions and net carbon sequestration of “Grain for Green” Program in China. Chin J Appl Ecol 27:1693–1707

Lu B, Kong SF, Han B et al (2011) Inventory of atmospheric pollutants discharged from biomass burning in China continent in 2007. Chin Environ Sci 31:186–194

Ma ZH, Pan ZQ, He HM (1999) Greenhouse gas emission factor for coal power chain in China and the comparison with nuclear power chain. Chin J Nucl Sci Eng 19:268–274

MIITPRC (Ministry of Industry and Information Technology of the People’s Republic of China) (2010) Woven wire fencing. China Machinery Press, Beijing

NBS (National Bureau of Statistics), NDRC (National Development and Reform Commission) (2013) China energy statistical yearbook 2013. Standards Press of China, Beijing

NSPRC (National Standards of the People’s Republic of China) (1995) The state technical standard of chemical weed control in main plantation trees. Standards Press of China, Beijing

NSPRC (2005) Technical regulation for afforestation by aerial seeding. Standards Press of China, Beijing

NSPRC (2006) Artificial afforestation technical regulations. Standards Press of China, Beijing

NSPRC (2009) Regulation for tending of forest. Standards Press of China, Beijing

Ren JS, Chu JL, Wang Q et al (1999) The comparison of CA141 and EQ140 automobile in log transportation and produciton for forest region. Forestry Mach Wood Equip 27:21–22

RIWI (Research Institute of Wood Industry), CAF (Chinese Academy of Forestry) (1982) Wood physical and mechanical properties of major tree species in China. Chinese Forestry Publishing House, Beijing

Shi SL (2009) Technical guidelines of grassland work. Jindun Press, Beijing

Tian YH, Zhu QH, Geng Y (2013) An analysis of energy-related greenhouse gas emissions in the Chinese iron and steel industry. Energ Policy 56:352–361

Wang SX, Wei W, Du L et al (2009) Characteristics of gaseous pollutants from biofuel-stoves in rural China. Atmos Environ 43:4148–4154

Wang YL, Zhu QH, Geng Y (2013) Trajectory and driving factors for GHG emissions in the Chinese cement industry. J Clean Prod 53:252–260

Xu GF, Yu QG, Sun YQ et al (2010) Technology and measures of forest tending and management in new period. For Invent Plan 139:131–134

Xue W, Zhang CH (2009) Operation efficiency of tending machineries to plantation of Larix dahurica. Jilin Forestry Sci Technol 38:13–18

Zhang HW, Lei YP (2010) New technology of aerial afforestation and silviculture in Henan. The Yellow River Water Conservancy Press, Zhengzhou

Zheng XH, Han SH, Huang Y et al (2004) Requantifying the emission factors based on field measurements and estimating the direct N2O emission from Chinese crop lands. Glob Biogeochem Cycles. doi:10.1029/2003GB002167

Zhou HS, Ao AQ (2014) Typical technology mode of “Grain for Green”. China Forestry Publishing House, Beijing

Zhou Y, Li D, Wu ZL et al (2014) Carbon emission in forest logging operation process. Forest Eng 30:1–5