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Supplementary Materials for

Carbon emissions from land-use change and management in China between 1990 and 2010

Li Lai, Xianjin Huang, Hong Yang, Xiaowei Chuai, Mei Zhang, Taiyang Zhong, Zhigang Chen, Yi Chen, Xiao Wang, Julian R. Thompson

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Supplementary Materials

Supplementary Materials and Methods

Land-use category and area

This study employed a land-use dataset acquired from the National Resources and Environment Database of the Chinese Academy of Sciences (CAS). This dataset is based primarily on Landsat TM imagery from 1990, 1995, 2000, 2005 and 2010. The LUCC classification of CAS was adopted. This approach combines Landsat TM images and auxiliary data (i.e. temperature, precipitation, elevation) along with the calibration from field survey (*59*). The land-use types were classified into six categories: farmland, forest, grassland, water, built-up land and other land (table S1). A digital climate type map for use in this classification was made using the 1:3.6 million Chinese climate zoning map (*60*), divided into tropical, subtropical, temperate-wet, temperate-dry and plateau climatic zones.

Calculation of vegetation carbon storage change

The digital vegetation type map was made using the 1:1 million Chinese vegetation map (*53*), with vegetation classified according to 50 different classes. The values of carbon density for each vegetation types were collected from published results (table S7). Carbon emission from changes in above ground and below ground biomass caused by land-use change was calculated using the following formula

$$\Delta C_{CONVERSION} = \sum_{i}[(B_{AFTERi} - B_{BEFOREi}) \times \Delta A_{TO\_OTHERSi}]$$

where $\Delta C_{CONVERSION}$ is the change in biomass carbon stocks on land converted to another land type; B_{AFTERi} is carbon stocks on land type *i* immediately after the conversion; $B_{BEFOREi}$ is carbon stocks on land type *i* before the conversion; $\Delta A_{TO\_OTHERSi}$ is the area of land-use *i* converted to another land type; *i* is type of land-use converted to another type.

Calculation of SOC storage change

The digital soil carbon map was made using the 1:1million Chinese soil type map (*54*) and SOC from China's 2nd National Soil Survey conducted from 1979–1985 (*22, 55, 56*). Due to data limitations, Taiwan was not included in this analysis. Comparing land-use category and area for each patch, we analyzed the soil carbon storage change caused by land-use conversion between 1990 and 2010. We used the Tier 1 method from IPCC (*58*). Different methods can be used to up-scale the SOC results. One study in Zhejiang Province, China found that the differences caused by four alternative methods (the mean, median, soil profile statistics and pedological professional knowledge) were in the range 0.5% - 10.6% (*61*). We used the soil profile statistics method to estimate SOC, and the error is considered less than 10.6%. The SOC storage change over this 20 year period was calculated using the formula

$$\Delta SOC = \sum_{C,S}(SOC_{REF_{C,S}} \times F_{IMPACT_{C,S}} \times A_{C,S})$$

where ΔSOC represents change of SOC stocks; SOC_{REF} represents SOC density with ground-based soil inventories data taken from soil profiles collected during the 2nd National Soil Carbon Survey. F_{IMPACT} represents the impact factors of SOC change (*23*) (see details in table S5); *c* represents the climate zones; *s* represents the soil types; and *A* represents land area of the stratum for which carbon stocks are being estimated. For analytical purposes all land in a given stratum should have common biophysical conditions (i.e. climate and soil type).

Calculation of carbon stock change from forestland management

Based on the 5th and 7th National Forest Inventory data (1994–1998 and 2004–2008), this study estimates carbon emissions due to forest consumption between 1994 and 2008. In this context forest consumption includes direct forest harvesting, fuel wood collection, forest fires and disaster losses (*57*). However, living stock volume consumption in the National Forest Inventory included wood harvesting from deforestation, which was also estimated in the land-use change analysis. Therefore, it was necessary to remove this volume consumption to avoid double counting. Here we calculate emissions due to forestland management as a function of consumption biomass volume, consumption rate, stem volume density (*SVD*) and biomass expansion factor (*BEF*), using the formula

$$\Delta C=(V\times CR-A_T\times D_V)\times SVD\times BEF\times 0.5$$

where ΔC represents the carbon loss from forest consumption; V represents living wood growing stock volume; CR represents forest consumption rate; A_T represents deforestation area, namely the land changed from forestland to other land-use type; D_V represents the living stock volume per hectare; SVD represents average stem volume density in a specific province; BEF represents biomass expansion factor, defined as the average ratio of all stand biomass to growing stock volume; 0.5 is the default value of carbon content in biomass. The specific parameters for each province or region are listed in tables S3 and S9.

Calculation of carbon stock change from farmland and grassland management

The carbon stock changes due to farmland and grassland managements were assessed using the empirical model recommend by IPCC (*58*). In this assessment, relative storage change factors for different management activities on farmland and grassland were taken from the literature (*27*, *62*), and SOC values were taken from the 2nd National Soil Survey. The carbon stock change was calculated using the formula

$$\Delta SOC=\sum_C (SOC_{REF_C}\times F_{LU_C}\times F_{MG_C}\times F_{I_C}\times A_C)$$

where ΔSOC represents change of SOC stocks; SOC_{REF} represents SOC density which were derived from thousands of soil profiles collected during 2nd National Soil Carbon Survey; F_{LU} represents the impact factors of land-use; F_{MG} represents the impact factors of land management; F_I represents the impact factors of nutrient inputs; c represents the climate zones; A represents land area of the stratum being estimated with, as described above, all land in a given stratum having common biophysical conditions (i.e. climate and soil type). The specific impact factor values for farmland and grassland management are listed in tables S5 and S6.

Supplementary Tables

table S1. Land-use categories. (*28*, *37*, *59*)

Top-lever categories	Sub-categories
1 Farmland	11 paddy field
	12 dry farmland
2 Forestland	21 wood land
	22 shrubbery land
	23 sparsely forested woodland
	24 other forest land
3 Grassland	31 high coverage grassland
	32 middle coverage grassland
	33 low coverage grassland
4 Water	41 river and canal
	42 lake
	43 reservoir and waterhole
	44 glacier and firn
	45 tidal marsh
	46 shoal and reed land
5 Built-up land	51 cities and towns
	52 rural settlements
	53 industry and traffic land
6 Other land	61 sandy land
	62 gobi
	63 saline-alkali land
	64 swampland
	65 bare land
	66 rock and gravel
	67 other unused land

table S2. Biomass and SOC change due to land-use category change in China between 1990 and 2010.

Region	Biomass carbon stock		SOC stock	
	From 1990-2010 TgC, 20a	Annual Change TgC	From 1990-2010 TgC, 20a	Annual Change TgC, a
North China	69.8	3.49	-0.3	-0.02
Northeast China	-28.1	-1.41	-98.6	-4.93
East China	-8.3	-0.42	-9.7	-0.48
Mid-south China	181.2	9.06	25.4	1.27
Southwest China	107.9	5.40	-69.7	-3.48
Northwest China	-58.1	-2.90	-77.1	-3.86
Total	264.3	13.22	-230.0	-11.50

table S3. Repeated calculation for part of forest consumption.

Region	Land transfer out from forest km^2	Stocking volume $m^3\ ha^{-1}$	SVD $t\ m^{-3}$	BEF
North China	30405	26.83	0.501	1.375
Northeast China	40255	73.43	0.501	1.402
East China	41573	36.21	0.423	1.428
Mid-south China	56893	27.61	0.443	1.443
Southwest China	46470	72.56	0.447	1.452
Northwest China	84011	27.68	0.471	1.440

Calculated from Table S5.

table S4. SOC impact factors for change in land-use conversion. (*62*)

Items	Forest land	Grassland	Farmland
Forest land		-10%	-27%
Grassland	Tropical 80%		-20%
	Sub-tropical 90%		
	Temperate 100%		
Farmland	Tropical 80%	100%	
	Temperate 90%		

table S5. SOC impact factors for Chinese farmland management. (*27*)

Factor	Level	Moisture regime	Cold temperate	Warm temperate	Tropical
			0<MAT<10	10<MAT<18	MAT>18
Land-use (F_{LU})	long term cultivated	Dry	0.80	0.80	0.58
		Wet	0.69	0.69	0.48
Tillage (F_{MG})	full	Dry	1.00	1.00	1.00
		Wet	1.00	1.00	1.00
	No-till	Dry	1.10	1.10	1.17
		Wet	1.15	1.15	1.22
Input（F_I）	fertilizer	Dry	0.95	0.95	0.95
		Wet	0.92	0.92	0.92
	Organic fertilizer	Dry	1.00	1.00	1.00
		Wet	1.00	1.00	1.00
	Straw returning with manure	Dry	1.04	1.04	1.04
		Wet	1.11	1.11	1.11

table S6. SOC impact factors for Chinese grassland management. (*62*)

Factor	Level	Climate regime	GPG revised default
Land-use (F_{LU})	all	all	1.00
	nominally managed	all	1.00
Management (F_{MG})	moderately degraded grassland	temperate/ boreal	0.95
		tropical	0.97
	severely degraded	all	0.70
	improved grassland	temperate/ boreal	1.14
		tropical	1.17
Input（F_I）applied to improved grassland	nominal	all	1.00
	high	temperate/ boreal	1.11
		tropical	1.11

table S7. Biomass carbon density of Chinese vegetation types.

Vegetation types	Carbon Density ($tC\ ha^{-1}$)	References
Boreal, temperate mountain deciduous coniferous forests	52.3	*(31)*
Temperate mountain evergreen coniferous forest	86.7	*(31)*
Temperate steppe sandy evergreen coniferous woodland	46.4	*(31)*
Temperate evergreen coniferous forest	22.4	*(31)*
Subtropical and tropical evergreen coniferous forest	17.4	*(31)*
Subtropical and tropical mountain evergreen coniferous forest	26.8	*(31)*
Temperate deciduous broadleaf - evergreen conifer mixed forest	48.0	*(31)*
Temperate, subtropical deciduous broadleaf forest	43.2	*(31)*
Temperate, subtropical deciduous microphylla forest	28.8	*(31)*
Temperate deciduous microphylla woodland	34.6	*(31)*
Sub-tropical limestone deciduous - evergreen broadleaf mixed forest	32.0	*(31)*
Subtropical mountain yellow-soil evergreen - deciduous broadleaf mixed forest	69.1	*(31)*
Subtropical evergreen broadleaf forest	59.2	*(31)*
Tropical rain forest of evergreen broadleaf forest	68.2	*(31)*
Subtropical evergreen sclerophyllous broadleaf forest	58.8	*(31)*
Subtropical Bamboo	34.4	*(63)*
Tropical semi-evergreen broadleaf forests and secondary vegetation	68.2	*(31)*
Tropical evergreen broadleaf forests and secondary vegetation	68.2	*(31)*
Temperate, subtropical deciduous shrub, coppice	6.2	*(64)*
Subtropical and tropical acid soil evergreen, deciduous broadleaf shrubs, coppice and meadow	17.0	*(64)*
Subtropical and tropical limestone evergreen , deciduous shrubs, coppice	12.1	*(64)*
Tropical evergreen broadleaf sclerophyllous coastal scrub, coppice	5.9	*(64)*
Tropical evergreen broadleaf shrub succulent coral reefs, coppice	5.9	*(64)*
Sub-tropical mountains, sub-alpine evergreen scoriaceous scrub, coppice	11.7	*(64)*
Temperate, subtropical sub-alpine deciduous scrub	7.7	*(64)*
Temperate alpine dwarf shrub tundra	3.3	*(65)*
Temperate, subtropical subalpine cushion-shaped dwarf shrubs, herbaceous vegetation	3.3	*(65)*
Temperate dwarf semi-shrubby desert	1.0	*(65)*
Temperate succulent holophytic dwarf semi-shrubby desert	1.0	*(65)*
Temperate shrubby and semi-shrubby desert	1.0	*(65)*
Temperate semi - arboreous desert	1.0	*(65)*
Temperate prostrate dwarf semi-shubby desert	1.2	*(65)*
Temperate grass and forb steppe	2.1	*(66)*
Temperate needlegrass steppe	2.1	*(66)*
Temperate mountain needlegrass steppe	2.1	*(66)*
Temperate dwarf needlegrass, semi-dwarf shrub steppe	2.1	*(66)*
Temperate mountain dwarf grass, semi-dwarf shrub steppe	2.1	*(66)*
Temperate, subtropical alpine steppe	1.8	*(65)*
Subtropical and tropical shrub savanna	3.4	*(29)*
Temperate meadow	3.7	*(65)*
Temperate and sub-tropical alpline meadow	1.8	*(65)*
Temperate herbaceous swamp	3.9	*(65)*
Temperate alpine herbaceous swamp	3.9	*(65)*
Cold-temperate cultivated vegetation	5.7	*(29)*
Dry-Temperate cultivated vegetation	5.7	*(29)*
Humid-temperate cultivated vegetation	5.7	*(29)*
Sub-Tropical cultivated vegetation	5.7	*(29)*
Tropical cultivated vegetation	5.7	*(29)*
Bare land/Ice/desert	0.0	*(29)*
Lake	0.0	*(29)*

table S8. SOC density of Chinese soil types. (*54*)

Soil type	SOC density (tC ha^{-1})	Soil type	SOC density (tC ha^{-1})
Laterite	9.23	Limestone soil	13.05
Crimson soil	9.15	Volcanic ash soils	13.76
Red soil	9.58	Purple soil	5.54
Yellow soil	10.51	Rockv soil	1.62
brown comferous forest soil	24.74	Skeleton soil	5.15
Grev soil	94.29	Meadow soil	14.43
Yellow brown soil	13.12	Shajiang black soil	7.07
Yellow cinnamon soil	6.7	Moutain meadow soil	26.91
Brown soil	12.81	Forest/shrub meadow soil	6.63
Dark brown soil	18.76	Tidal soil	6.54
Bleached beijiang soils	14	Bog soils	49.49
Drv red soil	9.2	Pearv soil	146.76
Cinnamon soil	8.25	Solonchak soil	6.36
GreV cinnamonic soil	13.38	Desertv solonchak soil	5.49
Black soil	15.42	Seashore solonchak soil	10.92
Grey forest soil	29.38	Acid sulphate soil	27.29
Chemozem	16.12	Frigid solonchak soil	4.15
Chestnut-like calcic soil	11.06	Alkali soil	5.33
Chestnut-like cinnamon soil	5.61	Paddv soil	11.14
Drak calcic soil	8.61	Irrigated alluvial soil	7.21
Calcic brown soil	4.25	Irrigated desert soil	9.52
Sierozem	5.28	Grass felt soil	14.79
Grev desert soil	3.6	Black grass felt soil	18.05
Grev brown desert soil	1.53	Cold calcic soil	6.08
Brown desert soil	1.15	Cool calcic soil	6.2
Yellow soft soil	3.98	Brown cool calcic soil	6.42
Red clav soil	5.3	Cold desert soil	3.56
Recent deposited soil	4.67	Cool desert soil	1.21
Takvr soil	3.21	Cold frozen soil	2.64
Wind sand soil	1.91		

table S9. Parameters for Chinese forest consumption.

Province	7th forest inventory (2004-2008) (*67*)				5th forest inventory (1994-1998) (*57*)			
	Biomass volume (10^4 m^3)	Consumption Rate (%)	*SVD* (t m^{-3})	*BEF*	Biomass volume (10^4 m^3)	Consumption Rate (%)	*SVD* (t m^{-3})	*BEF*
Beijing	1291.29	4.31	0.484	1.427	1115.25	3.28	0.504	1.58
Tianjin	277.01	9.44	0.423	1.470	250.46	4.49	0.507	1.69
Hebei	10183.91	4.89	0.478	1.430	7856.82	8.22	0.504	1.53
Shanxi	8846.96	2.21	0.484	1.467	8009.04	6.73	0.484	1.59
Inner Mongolia	136073.6	0.88	0.505	1.364	116859.43	1.47	0.486	1.45
Liaoning	21174.91	3.23	0.504	1.434	17362.63	1.73	0.518	1.59
Jilin	88244.21	1.91	0.505	1.411	82753.39	3.80	0.508	1.55
Heilongjiang	165191.6	1.67	0.499	1.393	156615.58	2.02	0.507	1.50
Shanghai	275.2	6.71	0.392	1.461	133.67	2.86	0.516	1.49
Jiangsu	5022.59	10.16	0.395	1.309	3633.57	14.40	0.278	1.55
Zhejiang	19382.93	4.46	0.406	1.421	12660.40	15.27	0.436	1.52
Anhui	16258.35	6.14	0.416	1.408	10441.14	5.71	0.436	1.62
Fujian	53226.01	5.63	0.436	1.441	41763.62	8.67	0.454	1.57
Jiangxi	45045.51	5.35	0.422	1.435	27695.69	6.94	0.461	1.53
Shandong	8627.99	9.51	0.412	1.428	6022.19	6.81	0.482	1.68
Henan	18051.16	6.86	0.488	1.392	13167.55	9.90	0.563	1.59
Hubei	23121.55	4.94	0.459	1.477	14759.04	8.04	0.480	1.51
Hunan	38177.2	6.38	0.394	1.387	23147.09	7.93	0.429	1.51
Guangdong	32160.74	7.18	0.474	1.513	21325.15	9.06	0.464	1.57
Guangxi	51056.78	5.90	0.430	1.448	31027.39	6.66	0.471	1.47
Hainan	7940.93	4.07	0.488	1.419	7281.49	4.20	0.495	1.58
Chongqing	13803.63	2.93	0.431	1.419	-	-	-	-
Sichuan	168753.5	1.06	0.425	1.419	154520.65	1.82	0.453	1.63
Guizhou	27911.53	3.70	0.425	1.480	17022.35	5.99	0.477	1.57
Yunnan	171216.7	2.25	0.501	1.488	142391.06	3.17	0.531	1.61
Tibet	227271.4	0.47	0.427	1.449	209063.72	0.42	0.376	1.70
Shaanxi	36144.16	2.28	0.558	1.517	33407.95	2.98	0.555	1.62
Gansu	21708.26	1.89	0.462	1.433	19224.52	3.34	0.495	1.65
Qinghai	4413.8	1.27	0.408	1.483	3728.46	1.24	0.425	1.67
Ningxia	625.93	3.30	0.444	1.445	674.17	14.78	0.432	1.59
Xinjiang	33914.5	1.55	0.393	1.356	28998.52	1.04	0.393	1.60

During the 5th Forest Inventory, Chongqing was still part of Sichuan Province.