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Carbon storage and its changes in Chinese terrestrial ecosystem in recent decades

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Abstract. This paper made a comprehensive assessment on carbon storage in terrestrial ecosystem in China by reviewing published literatures. Much more detailed carbon storages in vegetation, soil and ecosystem were summarized for forest, grassland, shrub, cropland and wetland in recent decades. It was discovered that total terrestrial carbon storage in China was 67.9 ~191.8 Pg C in recent decades, 6.1 ~ 57.57 Pg C was stored in vegetation, and 161.7 ~ 185.7 Pg C was stored in topsoil at a depth of 100 cm. Vegetation carbon storage has increased obviously in recent years; soil carbon storage declined in some areas owing to intensive land use, while it increased in other areas because of fertilizer application and reforestation. Total terrestrial carbon storage over China has increased in recent decades, and it is expected to continue to increase.

1 Introduction

Carbon in terrestrial ecosystems exists mainly in vegetation and soil in the form of organic or inorganic carbon[1]. Terrestrial carbon storage dynamics has attracted attention in recent years because it contributes to essential information about carbon budgets, which is important in predicting climate change. Several previous studies provided various estimates of terrestrial carbon storage across China[2-3]. However, different methods usually resulted in different estimates of carbon storage[4-7]. There exists uncertainty of the estimated terrestrial carbon storage because of climate change and anthropogenic activities altered biogeochemical cycles[8-9].

To obtain a comprehensive insight for terrestrial carbon storage in China, this paper will assess Chinese terrestrial carbon storage (including vegetation carbon and soil carbon) and its change trend. Much more detailed vegetation and soil carbon storage will be summarized for forest, grassland, cropland and wetland ecosystems by published literature. Uncertain estimates from data sources, methodology and unstable environments were discussed.

2 Methods

Vegetation carbon storage, soil carbon storage and terrestrial carbon storage in China were investigated by published literatures respectively. Terrestrial carbon is stored mainly in forest, grassland, shrub, farmland and wetland ecosystems. The detailed carbon storage in vegetation, soil and total terrestrial ecosystem were examined for forest, shrub, grassland, cropland and wetland ecosystems.

To explore the change of vegetation carbon storage, the average carbon storage was calculated for each specific period (1973–1976, 1977–1981, 1984–1988, 1989–1993, 1994–1998,1999–2003, 2004–2008) of seven national forest inventories. To examine the change of soil carbon storage, soil carbon storage was summarized at different soil depths. The terrestrial carbon storage and its dynamics in different periods was examined for Chinese forest, shrub, grassland, cropland and wetland ecosystems. In the end, the paper discussed the credibility of these estimates of carbon storage

3 Results

3.1 Vegetation carbon storage

3.1.1 Vegetation carbon storage in terrestrial ecosystem

In Mid-Holocene, there was the largest vegetation carbon storage of 70.6 Pg C in China. In recent decades, Chinese vegetation carbon storage was estimated of 6.1~57.9 Pg C according to different estimates methods in the published literature (Table 1).

Although there were disagreement about total vegetation carbon storage, lots of studies confirmed that vegetation carbon storage increased in recent years, since vegetation carbon storage increased in forest, shrub and

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farmland ecosystems [13-14]. Carbon from atmosphere was input vegetation systems at a rate of 1.8 Pg C/a in China according to the Carnegie-Ames-Stanford Approach (CASA), at a rate of 2.91~3.37 Pg C/a by the Lund–Potsdam–Jena Dynamic Global Vegetation Model (LPJ–DGVM), and at a rate of 3.12 Pg C/a by a remote sensing model [15-17]. In short, these studies provided an approximate input rate of 1.8 ~ 3.37 Pg C/a in recent decades. However, it is not clear how much carbon in vegetation was released into soil and atmosphere at the same period.

Table 1. Vegetation carbon storage in China

Period	Vegetation C Storage (Pg C)	Method	Spatial resolution	Reference
Last glacial maximum	15.5	Osnabrück model	0.5°	[5]
Mid–Holocene	70.6	Osnabrück model	0.5°	[5]
Present	57.9	Data–based estimates	0.5°	[5]
Present	6.1	Biogeographical model	–	[4]
1980s	57.57	BIOME3 model	10′	[10]
1980s	35.23	BIOME3 model &Baseline vegetation	–	[6]
1980s	53.96	BIOME3 model &Baseline biome	10′	[6]
1981–1998	13.33	CEVSA model	0.5°	[11]
1961–1990	14.04	AVIM2model	0.1°	[12]
2004-2014	14.60	Statistics		[84]

3.1.2 Vegetation carbon storage in different ecosystems

(1) Vegetation carbon storage in forest ecosystem

Vegetation carbon storage in Chinese forest ecosystem increased from 3.26 Pg C in 1949 to 11.49 Pg C in 2014, and the growth mainly resulted from forest expansion, for example forest area increased from 95.6 km^2 to 195.89 km^2 between 1949 and 2014 (Table 2). To explore the detailed change in forest carbon storage, we calculated average forest carbon storage for each period (1973~1976, 1977~1981, 1984~1988, 1989~1993, 1994~1998,1999~2003, 2004~2008) according to the results of seven national forest inventories in previous studies, and confirmed that carbon storage in Chinese forests increased obviously between 1949 and 2014 (Fig.1 & Table 2).

However, vegetation carbon storage in Chinese forests decreased to the lowest point in the 1970s because of massive disafforestation [18-20]. After the 1970s, forest carbon storage increased rapidly due to reforestation at a rate of 75 Tg C/a between 1977 and 2003, and a rate of 85.3~101.95 Tg C/a between 1989 and 2003 [13, 21]. It was forecasted that carbon storage in Chinese forests would increase at a rate of 1649.6 T g C/a between 2000 and 2025 under a policy scenario of returning farmland to forest [22]. Vegetation carbon storage in forest would increase to 10.23 Pg C in 2050 under continuous natural forest growth [23].

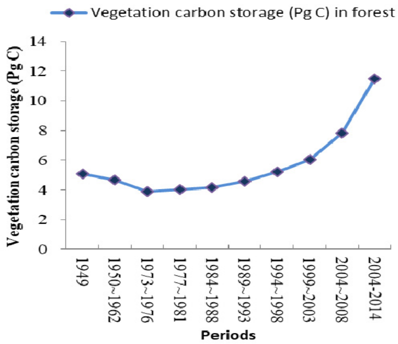

Fig.1. Vegetation carbon storages (average value of previous studies) in Chinese forest at different periods

(2) Vegetation carbon storage in grassland ecosystem

Vegetation carbon storage in Chinese grassland ecosystem was estimated of 1.04~4.66 Pg C by various studies [4,6,21] (Table3). According to national grassland survey in the 1980s, the highest estimate of vegetation carbon storage in grassland was 4.66 Pg C [6, 34], and the lowest estimate of vegetation carbon storage was 1.15 Pg C [4,13]. Vegetation carbon storage in grassland ecosystems did not change significantly, just a slight increase at a rate of 126.67 Tg C/a in recent decades [35-37].

(3) Vegetation carbon storage in shrub ecosystem

Vegetation carbon storage in Chinese shrub ecosystem was estimated of 30~35.34 Pg C by various studies [6]. Owing to protection and reforestation policy, shrub vegetation carbon increased obviously. The increase rate of net carbon in shrubs between 1981 and 2000 was estimated to be 14~24 Tg C/a by the CASA model [13], and 21.7±10.2 Tg C/a by satellite–based inventory [14].

(4) Vegetation carbon storage in cropland ecosystem

Vegetation carbon storage in cropland usually didn't count into total vegetation carbon storage because of annual harvesting. In fact, annual crops fixed huge carbon from atmosphere. It was discovered that annual crops absorbed 146 Tg C/a, 159 Tg C/a, 260 Tg C/a, 394 Tg C/a, and 513 Tg C/a in the 1950s, the 1960s, the 1970s, the 1980s and the 1990s respectively [40], which showed an increasing crops carbon markedly since the 1950s. Another study suggested vegetation carbon in cropland ecosystems increased at a rate of 12.5~14.3 Tg C/a in the period of 1982-1999 [13], and this increase mainly resulted from fertilizer application [41].

(5) Vegetation carbon storage in wetland ecosystem

There is no report about vegetation carbon storage in wetland at a national scale. However, a study showed that total carbon storage was 8~10 Pg C in Chinese wetland in recent years [42], and 15% of carbon was stored in vegetation in some wetlands [43]. Thus, it can be inferred that vegetation carbon storage was 1.2~1.5 Pg C in Chinese wetland. It was also reported that vegetation carbon storage in wetland was 0.20 Pg C in 2004-2014 [84]. Vegetation carbon storage in Chinese wetland decreased significantly because vast areas of wetland disappeared, but it was not clear how much vegetation carbon lost [28, 44].

Table 2. Vegetation carbon storage in Chinese forest ecosystem

Period	Data source	Forest area (10^6ha)	Carbon torage (Pg C)	Methods	Reference
1949	Estimated data	102.34	5.06	Improved volume biomass method	[24]
1950~1962	Estimated data	98.08	4.67	Improved volume biomass method	[24]
1973–1976	The 1st investigation	96.03	3.75	Volume biomass method	[19]
1973–1976	The 1st investigation	101.26	4.44	Improved volume biomass method	[24]
1973–1976	The 1st investigation	105	3.51	Age–base volume biomass method	[25]
1973–1976	The 1st investigation	108.22	3.85	Age–base volume biomass method	[26]
1977–1981	The 2nd investigation	95.63	4.12	Volume biomass method	[19]
1977–1981	The 2nd investigation	95.62	4.38	Improved volume biomass method	[24]
1977–1981	The 2nd investigation	95.6	3.6	Age–base volume biomass method	[25]
1977–1981	The 2nd investigation	116.5	4.3	Continuous biomass expansion factor method	[13]
1977–1981	The 2nd investigation	95.62	3.7	Age–base volume to biomass method	[26]
1984–1988	The 3rd investigation	118.46	4.55	Volume biomass method	[27]
1985–1988	The 3rd investigation	102.2	4.06	Volume biomass method	[19]
1984–1988	The 3rd investigation	102.19	3.26	Volume derived method	[8]
1984–1988	The 3rd investigation	102.19	3.72	Age–base volume biomass method	[28]
1984–1988	The 3rd investigation	102.19	4.45	Improved volume biomass method	[24]
1984–1988	The 3rd investigation	102.2	3.69	Age–base volume biomass method	[25]
1984–1988	The 3rd investigation	102.19	3.76	Age–base volume biomass method	[26]
1984–1988	The 3rd investigation	124.2	4.46	Continuous biomass expansion factor method	[13]
1984–1988	The 3rd investigation	102.19	5.71	Mean biomass density method	[29]
1984–1988	The 3rd investigation	102.19	4.02	Continuous biomass expansion factor method	[29]
1984–1988	The 3rd investigation	102.19	4.19	Mean ratio method	[29]
1989–1993	The 4th investigation	108.62	6.2	Volume biomass method	[30]
1989–1993	The 4th investigation	108.64	4.2	Volume biomass method	[19]
1989–1993	The 4th investigation	108.63	4.63	Improved volume biomass method	[24]
1989–1993	The 4th investigation	108.6	4.02	Age–base volume biomass method	[25]
1989–1993	The 4th investigation	108.64	3.78	Volume derived method	[31]
1989–1993	The 4th investigation	108.64	3.78	Volume derived method	[32]
1989–1993	The 4th investigation	108.64	4.11	Age–base volume biomass method	[26]
1989–1993	The 4th investigation	Unknown	4.22	Volume biomass method	[21]
1989–1993	The 4th investigation	108.64	4.45	Continuous biomass expansion factor method	[29]
1989–1993	The 4th investigation	108.64	6.03	Mean biomass density method	[29]
1989–1993	The 4th investigation	108.64	4.71	Mean ratio method	[29]
1994–1998	The 5th investigation	105.82	4.75	Improved volume biomass method	[24]
1994–1998	The 5th investigation	129.2	4.66	Age–base volume biomass method	[26]
1994–1998	The 5th investigation	Unknown	4.65	Volume biomass method	[21]
1994–1998	The 5th investigation	129.2	5.02	Continuous biomass expansion factor method	[29]
1994–1998	The 5th investigation	129.2	7.11	Mean biomass density method	[29]
1994–1998	The 5th investigation	129.2	5.21	Mean ratio method	[29]
1999–2003	The 6th investigation	142.79	5.51	Age–base volume biomass method	[26]

1999–2003	The 6th investigation	Unknown	5.16	Volume biomass method	[21]
1999–2003	The 6th investigation	142.79	5.86	Continuous biomass expansion factor method	[29]
1999–2003	The 6th investigation	142.79	7.73	Mean biomass density method	[29]
1999–2003	The 6th investigation	142.79	6.21	Mean ratio method	[29]
2004–2008	The 7th investigation	195.45	7.81	Biomass regression model	[33]
2004-2014	Published literature and investigation data	195.89	11.49	Statistics	[84]

Table 3. Vegetation carbon storage in Chinese grassland ecosystem

Period	Grassland area 10^4km^2)	Grassland classification	Vegetation C storage(Pg C)	Data source	Methods	Reference
1980s	569.9	8	1.23	land use and an agricultural atlas	Biomass method	[4]
1980s	405.87	11	4.66	vegetation map of China (1982)	Carbon density–area method	[6]
1981~1988	298.97	18	3.06	National grassland survey	Carbon density–area method	[34]
1981~1998	263.26	2	3.35	Global data of climate, soil and NDVI	CEVSA model	[11]
1981~1988	331.41	17	1.04	National grassland survey and remote sensing	Statistical model	[38]
1981~1988	334.1	17	1.05	National grassland survey and remote sensing	Statistical model	[35]
1981–1988	331.41	17	1.15	National grassland survey	Biomass method	[13]
1981–1988	330.995	18	3.32	National grassland survey and supplement	Biomass method	[39]
2004-2014	280.44		1.94	Published literature and investigation data	Statistics	[84]

3.2 Soil carbon storage

3.2.1 Soil carbon storage in terrestrial ecosystem

Soil carbon (SOC and SIC) storage in Chinese terrestrial ecosystems was estimated of 161.7~185.7 Pg C at a depth of 100 cm by a detailed national soil inventory [4, 45]. The maximum soil carbon storage (SOC and SIC) was estimated to be 382.1 Pg C over the entire soil profile [45].

SOC storage was estimated of 23.8~27.4 Pg C, 50~185 Pg C and 82.65~147.9 Pg C for vertical soil depths of 0-20 cm, 0-100 cm and >100 cm respectively according to different studies (Table 4). For the spatial distribution of SOC, the largest storage of SOC (23.60 Pg C) was seen in Southwest China [46].

SIC storage was estimated to be 77.9 Pg C at a depth of 100 cm and 234.2 Pg C in the entire soil profile according to some studies [45]. An estimate of SIC storage was 53.3±6.3 Pg C at a depth of 200 cm, and 60 Pg C at a depth of 250 cm by other studies [47, 60].

There were opposing arguments about changes in soil carbon storage. It was discovered that soil carbon storage declined owing to agricultural reclamation beginning in the 1950s in some regions [61-64], which led to a net loss of 2.86 Pg C in the last 20 years [59]. However, soil carbon storage increased at a rate of 105~198Tg C/a for SOC and 7~138Tg C/a for SIC in recent decades [65]. It was also reported that SOC in farmland increased at a rate of 23.61 Tg C/a because of fertilizer application; SOC in forests has increased at a rate of 11.72 Tg C/a because of reforestation [59].

3.2.2 Soil carbon storage in different ecosystems

(1) Soil carbon storage in forest ecosystem

SOC storage at soil depth of 100 cm was 15.04~34.23 Pg C in forest ecosystem. For different soil depths, SOC in Chinese forests was estimated of 5.2 Pg C, 8.91 Pg C, 10.89 Pg C, 13.04 Pg C and 15.04 Pg C at soil depths of 0–10 cm, 0–20 cm, 0–30 cm, 0–50 cm and 0–100 cm respectively in the 1980s [51]. For average soil depths of 17.3 cm, 81.9 cm and 99.2 cm, SOC in Chinese forest was 13.67 Pg C, 20.56 Pg C and 34.23 Pg C respectively in the 1980s [59]. It was estimated 22.59 Pg C for soil depth of 0-100 cm in 2004-2014 by published literature and investigation data [84]. There was no report about total soil carbon storage (SOC and SIC) in Chinese forests, but total soil carbon storage must be larger than SOC of 15.04~34.23 Pg C.

Soil carbon storage in Chinese forests changed due to the variability in forest area in recent decades. It was reported that soil carbon storage in forest decreased at a rate of 122 Tg C/a owing to forest shrinkage during 1950-1987, and then increased at a rate of 176.7 Tg C/a owing to forest expansion during 1988-2001[14, 66-67].

(2) Soil carbon storage in shrub ecosystem

Soil carbon storage in Chinese shrub was estimated of 9.1~13.6 Pg C at a depth of 0-100 cm in recent decades by different studies [50-51, 68, 84]. Likely, soil carbon storage in Chinese shrub has increased since the 1980s owing to large scale shrub recovery. It was reported that soil in shrub land has become the largest soil carbon sink (39 Tg C/a) among Chinese ecosystems since the 1980s [14].

(3) Soil carbon storage in grassland ecosystem

Soil carbon storage in Chinese grassland was estimated to be 23.75~74.74 Pg C by different methods. The highest estimate of soil carbon storage in grassland was up to 74.74 Pg C by the biomass method [4]. The lowest estimate of soil carbon storage in grassland was

23.75 Pg C by published literature and investigation data [84]. Carbon storage in Chinese grassland ecosystem remained relatively stable, though some change was seen in regional soil due to disturbance from human and climate over the past 20 years [36-37].

(4) Soil carbon storage in cropland ecosystem

SOC in cropland was 5.1 Pg C in topsoil (0-30 cm) according to the 2nd national soil survey in 1979–1982, but it was not clear how much SIC in cropland ecosystem [69]. There was a large soil carbon storage of 15.17 Pg C at soil depth 0-100 cm in cropland in 2004-2014 according to published literature and investigation data [84].

There were conflicting arguments about the change of soil carbon storage in cropland. It was reported that approximately 51% of cropland experienced carbon loss, and there was a loss rate of 15 t C/ha from 1979 to 1982, and a loss rate of 73.8 Tg C/a from 1995 to 1998 [64, 69-70]. On the contrary, it was reported that soil carbon in most croplands (81%) increased at a rate of 15 Tg C/a, 25 Tg C/a and 33 Tg C/a in the 1980s, the 1990s and the 2000s, respectively [71]. Improved crop management (including practices such as straw return into soil, organic fertilizer application, and reduced tillage practices etc.) contributed to the increase [41].

(5) Soil carbon storage in wetland ecosystem

There lacks of reports about soil carbon storage in Chinese wetlands at a national scale. Nevertheless, there is available information that total carbon storage was around 8~10 Pg C in Chinese wetland in recent years [42], and there was a ratio 84.54%~99.53% of soil carbon to total carbon in wetland [43]. It therefore could be inferred that soil carbon storage in Chinese wetland was 6.76~9.95 Pg C. Another report suggested that there was only 3.41 Pg C in wetland soil in 2004-2014 [84].

Unfortunately, soil carbon storage in wetland decreased greatly due to wetland's shrinkage since the 1950s [28, 44, 72]. For example, 3×10^4 km^2 of marshland in Northeast China has been destroyed, resulting in a loss of 218~240 Tg C [73-74]. However, not all wetlands suffered a loss of soil carbon. Soil carbon storage has increased by 101.61 Tg C in paddy soil, and 129.06 Tg C in fluvo–aquic soil from the 1980s to the 2000s owing to an increase in the use of chemical fertilizers [59].

3.3 Total terrestrial carbon storage

3.3.1 Total carbon storage in terrestrial ecosystem

Total carbon storage in terrestrial ecosystem over China was estimated of 67.9 ~ 191.8 Pg C, with an average terrestrial carbon storage of 158 Pg C in recent years (Table 5). For ancient historical carbon storage in China, it was estimated only 67.9 Pg C (1.55 Pg C in vegetation and 52.4 Pg C in soil) by an empirical Osnabrück biosphere model in the last glacial maximum, then increased to 183.4 Pg C (70.6 Pg C in vegetation and 112.8 Pg C in soil) in the mid–Holocene, then decreased to 157.9 Pg C (57.9 Pg C in vegetation and 100 Pg C in soil) until the modern period [5]. However, the estimates may not be accurate because these estimations derived from presumptive information on palaeovegetation and palaeoclimate with coarse spatial resolution of 0.5°×0.5°grid level [6].

In the present age, total terrestrial carbon storage was estimated 95.98 Pg C (13.33 Pg C in vegetation and 82.65 Pg C in soil) in China by the CEVSA (Carbon Exchange between Vegetation, Soil and Atmosphere) model [21]. However this model was based on data from a global database with a coarse spatial resolution, so it may not be accurate.

More credible terrestrial carbon storage were available owing to a series of ecological surveys and observational studies on national scale in recent years [68]. The total terrestrial carbon storage over China varied widely by different methods. For example, total terrestrial carbon storage in China was estimated to be 191.8 Pg C (6.1 Pg C in vegetation, and 185.7 Pg C in soil) by field samples of net primary production (NPP) [4], 154.99 Pg C by the latest climate and baseline vegetation data, 153.43 Pg C, 158.08 Pg C and 158.54 Pg C with grid cells of 10′, 20′ and 30′ respectively by the Biome model [6]. The lowest estimation in terrestrial carbon storage was 99.15 Pg C (14.60 in vegetation and 84.55 in soil) in 2004-2014 according to published soil organic carbon data [84]. These terrestrial carbon storages might be underestimated, because soil carbon storage below 100 cm is not calculated usually [75], and vegetation carbon storage in protected farmland forests, bamboo forests and other economical important forests was often ignored [13].

Total terrestrial carbon storage over China has increased obviously in recent decades. The increase in terrestrial carbon storage mainly resulted from the increase in vegetation carbon storage due to fertilizer application and expansion of forest and shrub [13, 21, 41]. The terrestrial ecosystem in China got 1.8~3.37 Pg C/a from vegetation photosynthesis [15, 17], with a net increasing rate of 96.1~106.1 Tg C/a in recent decades [13-14]. It was forecast that Chinese terrestrial carbon storage would increase 5.09~15.91 Pg C in the future under climate scenarios that predict CO_2 concentration of 340–500 ppmv [6].

Table 4. Soil organic carbon (SOC) storage in China

Study area	Soil area (10^4 km^2)	Soil depth (cm)	Soil profile	SOC storage (Pg C)	SOC density (kg C m^{-2})	Data source	Method	Reference
Whole China	9 44.86	0–100	725	185	19.05			[4]

Whole China	915	0–100	2500	50	2.7~16	Soil species of China	C–S	[47]
Whole China	881.81	0–100	34411	70.31	8.01	The 2nd survey	C–S	[48]
Whole China	923.97	0–100	2 456	84.4	1.2~176.5	The 2nd survey	C–S	[49]
Whole China	923.97	0–20	2 456	27.4	0.27~53.5	The 2nd survey	C–S	[49]
Whole China	868 veg	0–20	2 440	23.81	2.67	The 2nd survey	C–V	[50]
Whole China	868 veg	0–100	2 440	69.38	8.23	The 2nd survey	C–V	[50]
Whole China	901.6cov	0–100	2473	82.5	4.65~17.32	The 2nd survey	C–L	[51]
Whole China	928.1	0–100	7292	89.14	9.6	The 2nd survey	C–S	[52]
Whole China	880.37	0–100	3283	69.1	7.8	The 2nd survey	C–S	[53]
Whole China	928.1	0–100	7292	89.14	9.6	The 2nd survey &observation	C–S	[46, 54]
Whole China	918	0–100	2456	83.8	9.13	The 2nd survey & collection	C–S	[45]
Whole China	918	0–300	2456	147.9	16.11	The 2nd survey & collection	C–S	[45]
Whole China	896	0–100	2387	102.3	–	The 2nd survey	C–S	[55]
Whole China	959.63	–	–	119.76	7~28	Climate, soil & vegetation	BIOME3	[6]
Whole China	901.14	–	–	82.65	91.7	Climate, soil & vegetation	CEVSA	[11]
Whole China	925.64	0-100		84.55	9.13	Published soil organic carbon data	C–S	[84]
Main land of China	925.45	0–100	236	100.18	10.83	The 1st survey	C–S	[56]
Main land of China	877.63	0–100	2473	92.42	10.53	The 2nd survey	C–S	[57]
Main land of China	878	0–100	2473	92.4	10.53	The 2nd survey	C–S	[58]
Main land of China	870.94	0–100	2473	89.61	2.5~13.5	The 2nd survey & published	C–S	[59]

Table 5. Total carbon storage in Chinese terrestrial ecosystem

Period	Biome Number	Veg_C_ Storage (Pg C)	Soil_C_storage	Total_C_storage	Method	Spatial resolution	Reference
			(Pg C)	(Pg C)			
Last glacial maximum	7	15.5	52.4	67.9	Osnabrück model	0.5°	[5]
Mid–Holocene	9	70.6	112.8	183.4	Osnabrück model	0.5°	[5]
Present	9	57.9	100	157.9	Data–based estimates	0.5°	[5]
Present	32	6.1	185.7	191.8	Biogeographical model	–	[4]
1980s	18	57.57	118.28	175.83	BIOME3 model	10′	[10]
1980s	37	35.23	119.76	154.99	BIOME3 & Baseline vegetation	–	[6]
1980s	18	53.96	117.84	171.8	BIOME3 & Baseline biome	10′	[6]
1980s	18	–	–	153.43	BIOME3 model	10′	[6]
1980s	18	–	–	158.08	BIOME3 model	20′	[6]
1980s	18	–	–	158.54	BIOME3 model	30′	[6]

1981–1998	13	13.33	82.65	95.98	CEVSA model	0.5°	[11]
2004-2014		14.60	84.55	99.15	Statistics		[84]

3.3.2 Total carbon storage in main terrestrial ecosystems

(1) Total carbon storage in forest ecosystem

Carbon storage in Chinese forest ecosystem was estimated of 28.12 Pg C (6.2 Pg C in vegetation, 0.89 Pg C in litter and 21.02 Pg C in soil) according to detailed data from the Chinese Ministry of Forestry from 1989 to 1993 [30]. With the expansion of forest area, carbon storage in forest ecosystem has increased to 34.08. Pg C (11.49 Pg C in vegetation, 22.59 Pg C in soil) with forest area of 195.89×10^4 km^2 in the period of 2004-2014 [84].

Chinese forests were a carbon source, with a loss rate of 21Tg C/a from 1900 to 1949, but it became a carbon sink with a sequestration rate of 176.7 Tg C/a from 1988 to 2001 because forest experienced an expansion [66]. It was forecasted that forests had a net carbon sequestration rate of 97.6 M t C/a, and approximately 9 Gt C would be accumulated in forest ecosystems during the period of 1990–2050 [76].

(2) Total carbon storage in grassland ecosystem

There was different grassland area by previous studies, varied between 263.26×10^4 km^2 and 569.9×10^4 km^2 [4, 6, 21]. Therefore, the total carbon storage in grassland varied greatly. The total carbon storage in Chinese grassland ecosystem was estimated of 44.09 Pg C (3.06 Pg C in vegetation and 41.03 Pg C in soil) by a nationwide grassland resource survey in 1991 [34]. The total carbon storage in grassland ecosystem was estimated of 25.69 Pg C (1.94Pg C in vegetation and 23.75 Pg C in soil) with grassland area 280.44×10^4 km^2 in 2004-2014 by published soil organic carbon data [84].

In the past 20 years, neither vegetation carbon nor soil carbon in Chinese grassland ecosystem showed a significant change, though human activities could affect its carbon dynamics [36]. Nevertheless, carbon storage in Chinese grassland would increase by 4561.62 Tg C on conditions that the degraded grassland was recovered. Carbon sequestration would increase by a rate of 9.17 Tg C/a if some management practices were adopted, such as lower grazing intensity and enclosure restoration [77].

(3) Total carbon storage in shrub ecosystem

Shrub ecosystems cover an area of 215×10^4 km^2 in China [14]. The total carbon storage in shrub ecosystem varied obviously due to different estimation methods. Carbon storage in shrub ecosystem was estimated of 30.86 Pg C by baseline vegetation, and 29.34 Pg C, 34 Pg C and 34.72 Pg C as calculated with grids cell of 10′, 20′ and 30′ respectively by the Biome model [6]. The lowest carbon storage was estimated of 7.42 Pg C with shrub area of 77.69×10^4 km^2 in 2004-2014 according to published soil organic carbon data [84]. However, it was reported that carbon storage in Chinese shrub ecosystems kept an increase in recent years mainly owing to protection and reforestation policies [13-14].

(4) Total carbon storage in cropland ecosystem

Cultivated cropland covers an area of about 138×10^4~130×10^4 km^2 in China [69, 71]. Carbon storage in cultivated cropland was estimated of 30.55 Pg C in recent decades by baseline vegetation, 29.84 Pg C, 32.84 Pg C, and 32.93 Pg C as calculated with grid cells of 10′, 20′ and 30′ respectively by the Biome model [6]. Carbon storage in cropland was seen increasing markedly in recent half a century because of fertilizer application and improved management practices [40-41], but some cropland experienced carbon loss due to agricultural reclamation [64, 69-70].

(5) Total carbon storage in wetland ecosystem

Wetland ecosystems cover an area about 384 510 km^2 in China by the National Wetland Resource Inventory conducted in 2004 [42]. Carbon storage in Chinese wetlands was estimated of 8~10 Pg C in recent years. The lower estimation in wetland ecosystem was 3.62 Pg C with wetland area of 14.46×10^4 km^2 in 2004-2014 [84].

Unfortunately, carbon storage in wetland has been decreasing since the 1950s, with a total loss of approximately 1.5 Pg C over the last 50 years [42]. However, it is likely that protection and restoration policies will contribute to carbon sequestration by a rate of 30.48 G g C/a [78].

Table 6. Carbon storage in different terrestrial ecosystems in China

Ecosystem	Carbon storage (Pg C)	Reference
Forest	28.12	[30]
Grassland	29.1~44.09	[34, 36]
Shrubland	29.34~34.72	[6]
Farmland	29.84~32.93	[6]
Wetland	8~10 or 3.62	[42, 84]

4 Discussions

This paper examined various estimates for vegetation carbon storage, soil carbon storage, the total terrestrial carbon torage in recent years. These estimates have considerable uncertainty due to various data sources and methods, and unstable environments [55, 68].

4.1 Uncertainty of carbon estimation from data source

Traditional field investigations are regarded as reliable data source to estimate carbon storage. However, uncertain estimates also exist owing to differences in sampling techniques. Field sampling sites did not always follow the regular proportional spacing, and sample sites were lacking in some regions, such as the Tibetan plateau, desert regions and Taiwan province [36].

Two national soil surveys in the 1960s and the 1980s did not include Taiwan. Soil carbon storage in Taiwan was obtained by substitute methods, so the accuracy of estimates of soil carbon storage was likely low [48, 53]. Soil carbon storage in soil profiles beyond 100 cm was rarely documented at the national level, and a default soil depth of 100 cm was used in most estimates [45]. In many plains and plateaus, actual soil has a depth more than 100 cm, and the soil below 100 cm has abundant carbon, therefore soil carbon storage might be underestimated in many plains and plateaus. In many mountainous areas, actual soil depths are less than 100 cm [53, 79], so soil carbon storage might be overestimated.

For vegetation carbon storage, there lacks data of biomass carbon belowground, which was often gained indirectly from the ratio of aboveground biomass to belowground biomass [4, 36]. In most studies, carbon storage in scattered grasslands was ignored, which may have resulted in inaccurate calculation because scattered grasslands distribute widely in China [39]. Carbon storage in protected farmland forest, bamboo forest, and other economical important forest was also ignored [13]. As a result, vegetation carbon storage might be underestimated because of these uncalculated carbon in grasslands and forests. In addition, the definition of forest changed: prior to 1974, a forest was defined as having canopy coverage of 30%, whereas subsequently a forest was defined as having canopy coverage of 20% [13]. Thus, the increase of vegetation carbon storage in forest after the 1970s was likely caused partly by changed definition of forest.

4.2 Uncertainty of carbon estimation from different methods

Different methods usually led to different results about carbon storage even if the same data source was used. For example, SOC storage of forests calculated by the mean method was consistently higher than that calculated by the median method [80]. To estimate forest carbon storage, various different methods were used, such as the volume-derived method, the age-based volume biomass method, the continuous biomass expansion factor method, the mean biomass density method, the mean ratio method, and biomass regression model [8, 28-29, 32-33]. Therefore, these different methods often lead various estimates on carbon storage.

4.3 Uncertainty of carbon estimation from unstable environment

Climate change and anthropogenic activities have led to an unstable environment, which disturbed the geochemical cycle of terrestrial carbon [7]. Climate change significantly affects the rate of carbon accumulation and carbon release [14, 81], and anthropogenic activities cause significant change in carbon storage directly [79, 82-83]. For example, large scale deforestation occurred since the 1950s, which led to an obvious decrease in forest carbon storage; while large scale reforestation occurred since the 1980s, which led to a remarkable increase in forest carbon storage [14, 67, 84]. Thus, climate change and anthropogenic activities have resulted in an unstable environment, which makes it difficult to estimate carbon storage accurately.

5 Conclusions

Terrestrial carbon in China mainly exists in forest (28.12 Pg), grassland (44.09 Pg), shrub (29.34~34.72 Pg), cropland (29.84~32.93 Pg) and wetland (8~10 Pg) ecosystems. Vegetation carbon storage ranged from 6.1 to 57.9 Pg C based on various estimates. Soil carbon storage in China was estimated of 161.7~185.7 Pg C at a soil depth of 100 cm. Total terrestrial carbon storage was estimated to be 67.9 ~ 191.8 Pg C in recent decades in China. However, these estimates have considerable uncertainty due to various data sources and methods, and unstable environments. In recent decades, vegetation carbon storage has increased obviously owing to carbon increase in forest, shrub and farmland ecosystems. Soil carbon storage declined owing to intensive land use in some regions, but growth because of fertilizer application and reforestation. The total carbon storage in terrestrial ecosystem increased clearly in recent decades, and it is expected to continue to increase.

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