

Article

China's Tea Industry: Net Greenhouse Gas Emissions and Mitigation Potential

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Abstract: Tea is an important cash crop and a beverage that is widely consumed across the world. In China (the largest producer of tea), the industry is growing, and there is a need to understand current greenhouse gas (GHG) emissions and sequestrations and the potential for mitigation so that climate action can be strategically undertaken. Life cycle assessment and carbon footprint methods were used to quantify emissions in tea cultivation and processing in the 16 major producing regions for the year 2017. The system boundary was from cradle to factory gate, which was divided into three subsystems, namely agricultural materials production, tea production and tea processing. Several units of analysis were chosen: the production region (province), the production area (ha) and the product (kg loose tea), etc. Total GHG emissions were 28.75 Mt CO₂eq, which were mainly attributable to energy use in tea processing (41%), fertilizer production (31.6%) and soil emissions (26.7%). This equated to 12.0 t CO₂eq per ha and 10.8 kg CO₂eq per kg processed tea. Production in Hubei, Yunnan, Guizhou, Sichuan and Fujian provinces contributed almost two thirds of industry emissions, representing priority areas for strategic action to reduce GHG emissions. At the same time, the total carbon sink amounted to 21.37 MtCO₂, representing 74.3% of total GHG emissions. The proportions stored in soil, biomass, and tea production were 49.3%, 30.0%, and 20.7%, respectively. If best recommended management practices for fertilizer application were adopted and biomass was used as a source of energy for tea processing, the GHG emissions reduction potential was 16.66 Mt CO₂eq, or 58% of total emissions. The GHG emissions associated with tea production and processing in China appeared high by comparison to other regions of the world. However, considering the carbon sink and emissions reduction potential, the tea industry should be viewed as an important sector for climate action. Moreover, the potential for substantial GHG emissions reduction through the adoption of improved practices seems very realistic. There may also be additional opportunities for GHG emissions reduction through the development of organic tea cultivation systems.

Keywords: agriculture; carbon footprint; carbon sink; climate action; climate change; life cycle assessment

1. Introduction

In 2018, anthropogenic greenhouse gases (GHGs, including CO₂, CH₄, N₂O, and fluorinated gases) emissions exceeded 50 billion tons [1]. Urgent action is therefore needed to curb greenhouse gas emissions and avoid the most serious potential economic, social and environmental consequences of climate change. Agriculture is an important source of GHG emissions including carbon dioxide (CO₂), methane (CH₄) and nitrous oxide

(N₂O), amounting to 20–25% of total global emissions [2]. In turn, agricultural soils and cropping systems have potential as carbon sinks due to the ability to absorb carbon dioxide and store carbon. Lal [3,4], Burney et al. [5], Zhao [6] and Tang et al. [7] verified the carbon sink capacity of agricultural systems. However, balancing the goal of reducing agricultural GHG emissions while meeting the food demands of an increasing world population is a challenging task [8]. As stated by Borowski [9], each sector cannot be considered separately in the 21st century because sectors are interconnected. In addition, sustainability is a complex subject with inter-related economic and social warfare aspects in addition to environmental aspects that span climate change, water depletion and soil degradation, among others. Therefore, to realize sustainable development, a holistic view or an integrated framework including energy, economic, environmental and ecological factors should be established and used in agriculture and industry. For example, Biggs et al. [10] used the concept of “environmental livelihood security” to explore a sustainable balance between natural supply and human demand. The water, energy, food and climate change nexus is widely used in the context of social needs and economic development [9].

Globally, tea is one of the most important beverages due to its health functions [11,12], and the total area of tea cultivation and production have been increasing over recent decades. Tea is also an important cash crop in many parts of the world, supporting the livelihoods of smallholder farmers, especially in places like China, India and Sri Lanka. In 2018, the planting area and yield in the world amounted to 494×10^4 ha and 585×10^4 tons, respectively [13]. While tea production is not a GHG-emission-intensive agricultural sector, the scale at which tea is grown and consumed makes it an important focus for GHG emissions reduction. Already a variety of studies have been undertaken examining the energy efficiency, carbon footprint and environmental-economic analysis of tea production in India [14,15], Iran [16–18], Sri Lanka [19,20], Malawi [21], Turkey [22] and Kenya [23]. Cichorowski et al. [14], Doublet and Jungbluth [15], and Azapagic et al. [23] used the life cycle assessment method to analyze the greenhouse gas emissions of tea cultivation and consumption. Vidanagama and Lokupitiya [20], Taulo and Sebitosi [21], and Pelvan and Özilgen [22] explored energy consumption by the tea industry, and the results showed that electricity, diesel and biomass were major energy sources in tea processing, but coal was still used in some regions such as Turkey. Soheili-Fard [18] and Munasinghe et al. [19] made an integrated analysis including social, economic and environmental impacts of the tea sector in Iran and Sri Lanka, respectively. However, all these studies were focused on the regional level, and most did not consider the provision of ecological services. Certainly, some studies have investigated the ecological service potentials of tea plantation ecosystems. Li et al. [24] and Zhang et al. [25] evaluated carbon storage in China's tea plantations. Pramanik and Phukan [26] explored the ability of assimilating atmospheric CO₂ in tea gardens of northeast India. Kamau et al. [27] calculated the carbon and nutrient stocks of tea plantations, and Mishra and Sarkar [28] analyzed the relationship between the total organic carbon and soil carbon pools under different land management systems. However, there are few studies about the net carbon balance of the tea industry on a national level.

In China, in order to reduce poverty and support rural economies, tea cultivation has been expanding. Over the period 2008 to 2018, the planting area increased from 160×10^4 to 298×10^4 ha, and at the same time, the yield rose from 126×10^4 to 262×10^4 tons. In 2018, the area and yield of tea production in China were about 60% and 45% of the total area and yield in the world. Tea production is therefore becoming a mainstay industry in most of the tea-producing regions [11,29].

Concerning tea plantation and management, Ma et al. [30], Qian et al. [31], Ni [32] and He [33] investigated the status of fertilizer and pesticide use in Zhejiang, Anhui and Guizhou provinces, and Chongqing municipality, respectively. Ni et al. [34] also made an evaluation of fertilizer use and reduction potential in 14 provinces across China. Other researchers have focused on aspects of tea yield, quality [35–37] and soil health related to fertilization [38–40]. In addition, Wang et al. [41,42], Dai [43], Zhu et al. [44] and Zhang et al. [45] assessed the GHG emissions of tea gardens. Di [46], Cheng and Liao [47],

and Zhang et al. [48] assessed the energy consumption and carbon emissions related to tea processing. Xu et al. [49] examined the carbon footprint and primary energy demand of organic tea production in China and showed that although some regions such as Zhejiang and Fujian adopted cleaner energy sources such as electricity and biomass pellets for tea processing [49], most of the provinces, especially those in central and western regions, still depended heavily on coal [46–48].

Tea cultivation and processing are important agricultural industries in China. However, most of the presented research concerns specific local production systems or aspects of production. What is lacking is a national-level analysis of GHG emissions, carbon sink, and mitigation potential to identify priorities for targeted intervention. The objectives of this paper were (1) to make a macrolevel estimation of GHG emissions (including CO₂, CH₄, and N₂O) associated with the tea industry in China, including both tea cultivation and processing subsystems; (2) to quantify the C sink of tea plantation ecosystems and the GHG emissions reduction potential of the tea industry; and (3) to identify the key points for strategic intervention to enable the tea industry to contribute to global GHG emissions reduction.

2. Data and Methods

2.1. Data Sources

For the 16 major tea-producing provinces in China (Figure 1), data describing planting and picking areas, yields and product values for the year 2017 were sourced from the China Tea Yearbook (Table 1). Tea is also produced in Taiwan and Hainan; however, these provinces were excluded from the analysis due to the absence of data. For fertilizer inputs, data were sourced from surveys undertaken by Ni [32] and Ni et al. [34] for the major tea producing provinces (Table 2). These large-scale surveys assessed more than 6% of the total picking areas across the 16 provinces studied. For other farming inputs, such as diesel fuel consumption, pesticides and herbicides, data were sourced from Ni [32] and He [33]. Machinery, buildings and other capital items, which are not intensively used in tea cultivation, were not considered.

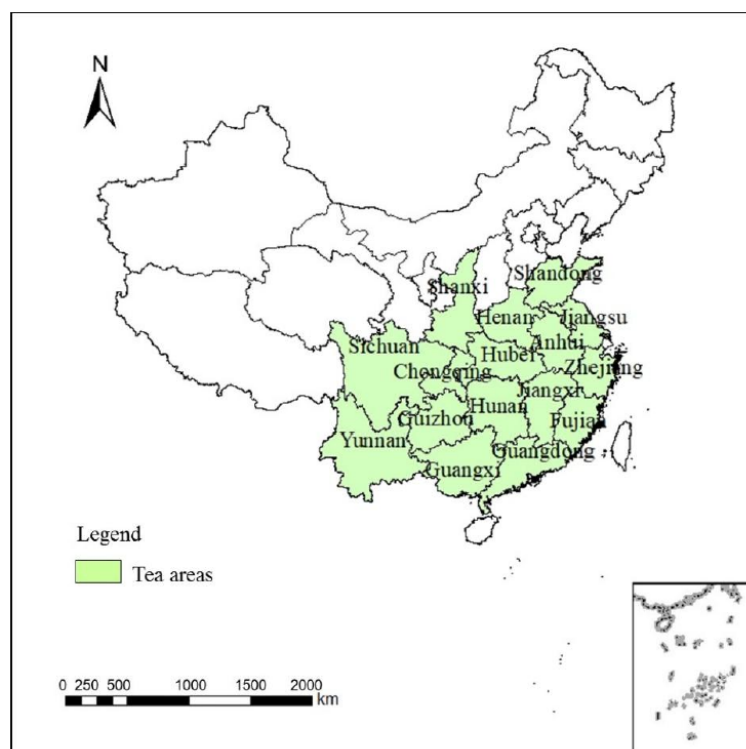


Figure 1. The main tea producing areas in China.

Table 1. Tea production in China in 2017.

Province	Planting Area (10 ⁴ ha)	Picking Area (10 ⁴ ha)	Production (10 ⁴ t)	Value (10 ⁸ USD)	Yield (kg ha ^{−1})
Guizhou	47.8	35.2	32.7	53.6	928
Yunnan	41.3	38.1	38.7	20.9	1016
Hubei	35.3	25.7	26.7	26.9	1039
Sichuan	33.3	24.4	28.0	31.1	1148
Fujian	25.3	24.1	44.0	34.8	1826
Zhejiang	20.0	17.9	17.9	28.7	1000
Anhui	18.0	14.7	13.4	16.5	912
Shanxi	16.7	10.1	8.9	18.9	881
Henan	16.0	11.7	6.7	17.9	573
Hunan	14.6	11.2	19.7	12.9	1759
Jiangxi	10.0	7.2	6.4	8.2	889
Guangxi	7.3	6.1	6.8	6.7	1147
Guangdong	5.7	4.3	9.5	5.9	2029
Chongqing	5.2	3.5	3.7	3.5	1057
Shandong	4.1	2.1	2.7	8.7	1286
Jiangshu	3.4	3.1	1.4	3.7	452
Total	304	239	267	298.8	1117

Data source: China tea yearbook in 2018.

Table 2. Nutrient applications in the main tea producing regions of China.

Province	Chemical Fertilizer (kg ha ^{−1})			Organic Fertilizer (kg ha ^{−1})			Total Nutrient (kg ha ^{−1})			Nutrient Ratio(N:P:K)
	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	
Guizhou	383	163	159	37	21	26	420	184	185	0.53:0.23:0.24
Yunnan	368	76	68	13	10	12	381	86	80	0.70:0.16:0.14
Hubei	708	112	112	37	21	24	745	133	136	0.73:0.13:0.13
Sichuan	573	107	105	54	40	49	627	147	154	0.67:0.16:0.17
Fujian	266	186	193	25	20	21	291	206	214	0.41:0.29:0.30
Zhejiang	410	93	110	57	27	27	467	120	137	0.65:0.17:0.18
Anhui	362	73	75	43	28	29	405	101	104	0.66:0.17:0.17
Shanxi	247	23	43	105	71	82	352	94	125	0.62:0.16:0.22
Henan	269	47	98	56	25	21	325	72	119	0.63:0.14:0.23
Hunan	606	164	135	68	40	45	674	204	180	0.64:0.19:0.17
Jiangxi	604	176	198	13	9	11	617	185	209	0.61:0.18:0.21
Guangxi	330	143	66	104	56	32	434	199	98	0.59:0.27:0.14
Guangdong	353	105	105	255	58	59	608	163	164	0.65:0.17:0.18
Chongqing	235	59	51	46	33	25	281	92	76	0.63:0.20:0.17
Shandong	536	203	233	190	282	729	726	485	962	0.34:0.22:0.44
Jiangshu	393	185	192	96	57	50	489	242	242	0.50:0.24:0.25
Mean	415	120	121	75	50	78	490	170	199	0.57:0.20:0.23

Source: Data for Guangdong and Guangxi provinces come from the authors' investigations; other regions from Ni [32] and Ni et al. [34].

In the tea processing stage, coal was the most common energy source in China, although some factories have begun to utilize electricity, natural gas and biomass. Energy use and energy cost data were sourced from Cheng and Liao [47], and Zhang et al. [48]. In this study, coal was regarded as the conventional source of energy and electricity; natural gas and biomass were regarded as alternative energy sources used to estimate GHG mitigation potentials.

2.2. Research Boundary and Method

Life cycle assessment (LCA) is an effective tool to evaluate the potential environmental impacts of a product, system or action [50,51]. As suggested by the name, LCA is distinguished by its life cycle perspective, taking account of the various forms of resource use and emissions that occur during the various stages of production, such as in farming and processing. In this study, LCA was used to evaluate net GHG emissions of China's

tea industry. Other non-GHG emissions and resource use were not assessed. The system boundary was from cradle to factory gate, which was divided into three subsystems, namely agricultural materials production (including fertilizers, pesticides, diesel, etc.), tea production (including transportation) and tea processing focused on energy consumption (Figure 2). As for the first and third subsystems, greenhouse gas emissions related to material production and energy consumption were considered. For the tea plantations, GHG emissions related to fertilization, pesticide use and diesel consumption for transportation were calculated. Moreover, the C sinks related to soils, increase in tea plant growth and tea production also were taken into account. As mentioned above, infrastructures such as buildings, roadways, etc. were not taken into consideration due to the absence of data. Due to a similar reason, only diesel consumption of transportation was calculated—and machines including vehicles were not taken into consideration—although it was widely used in modern agriculture. Several units of analysis were chosen: the production region (province), the production area (ha) and the product (kg loose tea). In addition, the GHG reduction potential under the best recommended management was considered, namely if optimized fertilization was practiced in tea plantation, and if coal, electricity, and natural gas were displaced by biomass energy in the stage of tea processing.

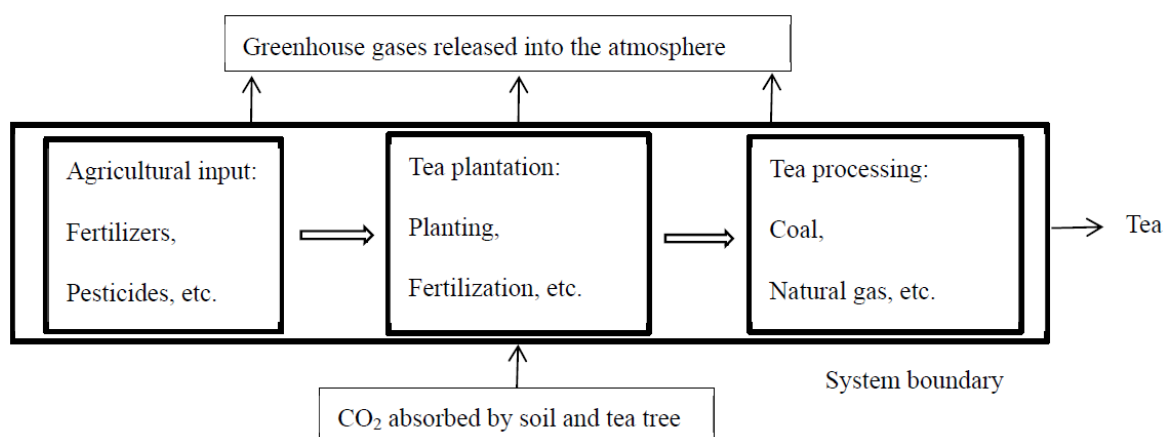


Figure 2. Flow diagram showing system boundary and stages of tea production.

2.3. Calculation of GHG Emission Sources

In the agricultural materials and tea production subsystems, GHG emissions related to the production of farming inputs (e.g., chemical fertilizers, pesticides) and fuel used in transportation were quantified according to Equation (1). The GHG emissions related to the application of chemical and organic fertilizers to soils at tea plantations [41,42] were quantified according to Equation (2). In the tea processing subsystem, Equation (1) was also used to quantify the GHG emissions associated with energy consumption. The total GHG emissions related to the system were quantified according to Equation (3). Emissions of CO₂, CH₄, and N₂O were aggregated using the 100-year global warming potential (GWP100) climate metric as described by Liang [51] and Liang et al. [50].

$$E_{fertilizer/garden/factory} = \sum (M_i * F_i) \quad (1)$$

$$E_{soil} = N_t * 0.014 * 1.57 * 298 \quad (2)$$

$$E_{total} = E_{garden} + E_{soil} + E_{factory} \quad (3)$$

where $E_{fertilizer/garden/factory}$ is the GHG emissions at fertilizers production, tea garden or tea processing factory caused by various material or energy consumptions; M_i is the amount of material or energy input i used; F_i is the emission factor of material or energy input i ; E_{soil} is the amount of GHG emission from application of fertilizer to soil at the tea garden; N_t is the total amount of nitrogen input; E_{total} is the total GHG emission

of tea production including fertilizers production, tea cultivation and processing. In addition, 0.014 is the emission coefficient of N_2O -N of soil [41], 1.57 and 298 are the transfer coefficients of N_2O -N to N_2O and N_2O to CO_2 eq, respectively.

2.4. Calculation of C Sinks

In this study, three C sinks were considered, namely carbon stored in soil, biomass, and tea produced in the tea plantation ecosystems. The C sink of soil was calculated according to Equation (4), and carbon stored in biomass and tea were estimated by Equations (5) and (6), respectively [24,52]. The total carbon storage was calculated according to Equation (7).

$$C_{\text{soil}} = \sum (A_i * C_{Ai} * 3.67) \quad (4)$$

$$C_{\text{garden}} = \sum (A_i * C_{Gi} * 3.67) \quad (5)$$

$$C_{\text{tea}} = \sum (Q_i * 0.45 * 3.67) \quad (6)$$

$$C_{\text{sink}} = C_{\text{soil}} + C_{\text{garden}} + C_{\text{tea}} \quad (7)$$

where A_i and Q_i are the picking area of tea plantation and quantity of tea production in region i , respectively, and C_{Ai} ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$) and C_{Gi} ($\text{Mg C ha}^{-1} \text{ yr}^{-1}$) are the average annual carbon change in soil and biomass in tea producing region i , respectively [24]. C_{sink} is the total C sink, and C_{soil} , C_{garden} , and C_{tea} are the amount of carbon stocked in soil, biomass and tea produced across the tea producing area in 2017, respectively. The numbers 0.45 and 3.67 are the C coefficient of tea production and the transfer coefficient of C to CO_2 , respectively.

2.5. Reduction Potential of Tea Industry

As for GHG emissions reduction potential, Ji et al. [38] and Ni [32] describe best recommend management (BRM) practices for tea cultivation in China. For fertilization, the recommendation is 350, 90 and 180 kg ha^{-1} of N, P_2O_5 and K_2O inputs, respectively, of which organic fertilizer inputs should amount to 25%. In the tea processing subsystem, opportunities for GHG emissions reduction relate to the substitution of energy from coal with cleaner energy sources, electricity, natural gas and biomass, as described by Cheng and Liao [47]. Equations (1)–(3) were used to evaluate the GHG emissions under BRM production scenarios and the GHG emissions reduction potentials were evaluated according to Equation (8).

$$E_{\text{potential}} = E_{\text{total}} - E_{\text{BRM}} \quad (8)$$

where $E_{\text{potential}}$ and E_{BRM} are the amount of GHG emissions reduction potential and the total GHG emissions under the BRM model.

3. Results

3.1. GHG Emissions of the Tea Industry

GHG emissions associated with the production of fertilizer inputs used in conventional tea cultivation are shown in Table 3 for the year 2017. Total GHG emissions for the 16 provinces amounted to 907×10^4 t CO_2eq , of which the greatest contributions came from Hubei (156.3×10^4 t CO_2eq), Guizhou (124.6×10^4 t CO_2eq), Yunnan (121.9×10^4 t CO_2eq) and Sichuan (121.1×10^4 t CO_2eq). The least contribution came from Chongqing municipality (7.2×10^4 t CO_2eq). On average, GHG emissions were 3.31 kg CO_2eq per kg tea production and 3.70 t CO_2eq per ha picking area, respectively.

Table 3. GHG emissions associated with the production of fertilizer inputs used in conventional tea cultivation and reduction potential under best recommended management.

Province	Conventional Model			Reduction Potential		
	Kg CO ₂ eq kg ⁻¹	T CO ₂ eq ha ⁻¹	10 ⁴ t CO ₂ eq Prov ⁻¹	Kg CO ₂ eq kg ⁻¹	T CO ₂ eq ha ⁻¹	10 ⁴ t CO ₂ eq Prov ⁻¹
Guizhou	3.82	3.54	124.6	1.45	1.34	47.3
Yunnan	3.15	3.20	121.9	1.05	1.07	40.6
Hubei	5.86	6.08	156.3	3.76	3.91	100.4
Sichuan	4.32	4.96	121.1	2.43	2.80	68.2
Fujian	1.45	2.65	63.8	0.25	0.45	10.9
Zhejiang	3.61	3.61	64.6	1.44	1.44	25.7
Anhui	3.46	3.15	46.3	1.11	1.01	14.9
Shanxi	2.39	2.10	21.2	0.07	0.06	0.6
Henan	4.14	2.37	27.8	0.42	0.24	2.8
Hunan	3.04	5.35	59.9	1.79	3.15	35.3
Jiangxi	6.08	5.41	39.0	3.61	3.21	23.1
Guangxi	2.60	2.99	18.2	0.74	0.85	5.2
Guangdong	1.55	3.16	13.6	0.48	0.98	4.2
Chongqing	1.95	2.07	7.2	0.00	0.00	0.0
Shandong	3.83	4.93	10.3	2.11	2.71	5.7
Jiangshu	8.16	3.69	11.4	3.28	1.48	4.6
Mean	3.31	3.70		1.46	1.63	
Total			907			390

In tea gardens, N₂O emissions from soils due to fertilization are an important GHG emissions source (Table 4). Total GHG emissions for the 16 provinces amounted to 769×10^4 ton CO₂eq, of which the greatest contributions came from Hubei (125.4×10^4 ton CO₂eq) and Sichuan (100.2×10^4 ton CO₂eq). On average, GHG emissions were 2.46 kg CO₂eq per kg tea production and 3.21 ton CO₂eq per ha.

Table 4. GHG emissions from soils for conventional tea cultivation and reduction potential under best recommended management.

Province	Conventional Model			Reduction Potential		
	kg CO ₂ eq kg ⁻¹	T CO ₂ eq ha ⁻¹	10 ⁴ t CO ₂ eq prov ⁻¹	kg CO ₂ eq kg ⁻¹	T CO ₂ eq ha ⁻¹	10 ⁴ t CO ₂ eq prov ⁻¹
Guizhou	2.54	2.75	96.8	0.49	0.46	16.1
Yunnan	2.11	2.50	95.1	0.20	0.20	7.7
Hubei	4.03	4.88	125.4	2.49	2.59	66.5
Sichuan	3.07	4.11	100.2	1.58	1.81	44.3
Fujian	0.89	1.91	45.9	0.00	0.00	0.0
Zhejiang	2.62	3.06	54.8	0.77	0.77	13.7
Anhui	2.49	2.65	39.0	0.40	0.36	5.3
Shanxi	2.24	2.31	23.3	0.01	0.01	0.1
Henan	3.18	2.13	24.9	0.00	0.00	0.0
Hunan	2.15	4.41	49.4	1.21	2.12	23.8
Jiangxi	3.90	4.04	29.1	1.97	1.75	12.6
Guangxi	2.12	2.84	17.3	0.48	0.55	3.4
Guangdong	1.68	3.98	17.1	0.83	1.69	7.3
Chongqing	1.49	1.84	6.4	0.00	0.00	0.0
Shandong	3.17	4.76	10.0	1.92	2.46	5.2
Jiangshu	6.07	3.20	9.9	2.01	0.91	2.8
Mean	2.46	3.21		0.78	0.87	
Total			769			209

Diesel and pesticide production and use for tea cultivation are shown in Table 5. In 2017, the total input of diesel and pesticide across the 16 provinces amounted to 5.15×10^4 tons and 180 t, respectively, and the corresponding GHG emissions were 17.1×10^4 and 3.2×10^4 ton CO₂eq, respectively.

Table 5. Diesel and pesticide inputs and GHG emissions related to tea cultivation in China.

Province	Agricultural Materials Input		GHG Emissions		
	Diesel (10 ⁴ t)	Pesticide (10 ⁴ kg)	Diesel (10 ⁴ t CO ₂ eq)	Pesticide (10 ⁴ t CO ₂ eq)	Subtotal (10 ⁴ t CO ₂ eq)
Guizhou	0.76	26.40	2.51	0.48	2.99
Yunnan	0.82	28.58	2.72	0.51	3.23
Hubei	0.55	19.28	1.83	0.35	2.18
Sichuan	0.52	18.30	1.74	0.33	2.07
Fujian	0.52	18.08	1.72	0.33	2.05
Zhejiang	0.38	13.43	1.28	0.24	1.52
Anhui	0.32	11.03	1.05	0.20	1.25
Shanxi	0.22	7.58	0.72	0.14	0.86
Henan	0.25	8.78	0.84	0.16	0.99
Hunan	0.24	8.40	0.80	0.15	0.95
Jiangxi	0.15	5.40	0.51	0.10	0.61
Guangxi	0.13	4.58	0.44	0.08	0.52
Guangdong	0.09	3.23	0.31	0.06	0.36
Chongqing	0.08	2.63	0.25	0.05	0.30
Shandong	0.05	1.58	0.15	0.03	0.18
Jiangshu	0.07	2.33	0.22	0.04	0.26
Total	5.15	179.6	17.09	3.23	20.3

Coal, electricity and natural gas are all used for tea processing in China, among which coal is the most popular energy choice. Biomass has been used as a lower-GHG-emission energy source in only a few factories. Table 6 presents the GHG emissions associated with meeting tea processing energy requirements using various energy options, i.e., coal ($1,178 \times 10^4$ ton CO₂eq), electricity ($1,507 \times 10^4$ ton CO₂eq), natural gas (668×10^4 ton CO₂eq) and biomass (111×10^4 ton CO₂eq). On the basis of per kg of tea, the GHG emissions associated with energy use in processing ranged from 0.42 to 5.64 kg CO₂eq, depending on the different energy sources, and the corresponding value per ha ranged from 0.47 to 6.30 ton CO₂eq (Table 7).

Table 6. GHG emissions and reduction potential based on different energy sources used for tea cultivation in China.

Province	Coal 10 ⁴ t CO ₂ eq	Electricity 10 ⁴ t CO ₂ eq	Natural Gas 10 ⁴ t CO ₂ eq	Biomass 10 ⁴ t CO ₂ eq	Coal-to- biomass 10 ⁴ t CO ₂ eq	Electricity- to-biomass 10 ⁴ t CO ₂ eq	Natural gas- to-biomass 10 ⁴ t CO ₂ eq
Guizhou	144.2	184.4	81.8	13.6	130.6	170.8	68.1
Yunnan	170.7	218.3	96.8	16.1	154.6	202.2	80.7
Hubei	117.7	150.6	66.8	11.1	106.6	139.5	55.6
Sichuan	123.5	157.9	70.0	11.6	111.8	146.3	58.4
Fujian	194.0	248.2	110.0	18.3	175.7	229.9	91.7
Zhejiang	78.9	101.0	44.8	7.4	71.5	93.5	37.3
Anhui	59.1	75.6	33.5	5.6	53.5	70.0	27.9
Shanxi	39.2	50.2	22.3	3.7	35.5	46.5	18.5
Henan	29.5	37.8	16.8	2.8	26.8	35.0	14.0
Hunan	86.9	111.1	49.3	8.2	78.7	102.9	41.1
Jiangxi	28.2	36.1	16.0	2.7	25.6	33.4	13.3
Guangxi	30.0	38.4	17.0	2.8	27.2	35.5	14.2
Guangdong	41.9	53.6	23.8	4.0	37.9	49.6	19.8
Chongqing	16.3	20.9	9.3	1.5	14.8	19.3	7.7
Shandong	11.9	15.2	6.8	1.1	10.8	14.1	5.6
Jiangshu	6.2	7.9	3.5	0.6	5.6	7.3	2.9
Total	1178	1507	668	111	1067	1396	557

Table 7. Tea production in China: GHG emissions and reduction potential related to different energy sources.

Functional Unit	GHG Emissions of Different Energy Sources				Reduction Potential Based on Different Energy Transformations		
	Coal	Electricity	Natural Gas	Biomass	Coal-to-Biomass	Electricity-to-Biomass	Natural Gas-to-Biomass
Per product (kgCO ₂ eq kg ^{−1})	4.41	5.64	2.51	0.42	3.99	5.22	2.09
Per area (ton CO ₂ eq ha ^{−1})	4.92	6.30	2.80	0.47	4.46	5.83	2.33

3.2. C sink of Tea Plantation Ecosystems

Total C sink of tea plantation ecosystems was 2137×10^4 t CO₂, and the specific amounts stored in biomass, soil and harvested tea were 1054×10^4 , 641.3×10^4 and 441.3×10^4 ton CO₂, respectively (Table 8). The corresponding proportions were 49.3%, 30.0%, and 20.7%, respectively. As for province, the greatest C sinks came from Yunnan (317×10^4 t CO₂), Fujian (298×10^4 t CO₂), Guizhou (288×10^4 t CO₂), Hubei (218×10^4 t CO₂), and Sichuan (208×10^4 t CO₂), respectively. The average C sink per ha picking area and per kg tea production were 8.93 t CO₂ and 7.99 kg CO₂, respectively.

Table 8. The C sink of tea plantation ecosystems in 2017 in China.

Province	Annual Biomass Increment 10 ⁴ t CO ₂	C Change in Soil 10 ⁴ t CO ₂	Harvested Tea 10 ⁴ t CO ₂	Total
Guizhou	158.9	74.9	54.0	287.8
Yunnan	172.0	81.1	63.9	317.0
Hubei	109.4	64.1	44.1	217.6
Sichuan	110.1	51.9	46.2	208.3
Fujian	108.8	116.8	72.7	298.2
Zhejiang	76.2	44.7	29.6	150.4
Anhui	62.6	36.7	22.1	121.4
Shanxi	43.0	25.2	14.7	82.9
Henan	49.8	29.2	11.1	90.1
Hunan	47.7	28.0	32.5	108.2
Jiangxi	30.7	18.0	10.6	59.2
Guangxi	27.5	29.6	11.2	68.3
Guangdong	19.4	20.8	15.7	55.9
Chongqing	15.8	7.5	6.1	29.4
Shandong	8.9	5.2	4.5	18.6
Jiangshu	13.2	7.7	2.3	23.2
Total	1054.0	641.3	441.3	2136.7

Considering C sinks of tea plantation ecosystems, the net GHG emission of tea industry would reduce from 2875×10^4 to 738×10^4 ton CO₂eq, and corresponding GHG emissions per ha picking area and per kg tea production would reduce to 3.08 t CO₂eq and 2.76 kg CO₂eq, respectively, which means net C footprint decreased by 74.3%.

3.3. Life Cycle GHG Emissions and Mitigation Potential

The life cycle GHG emissions (from cradle to factory gate after processing) of tea production in 2017 were $2,875 \times 10^4$ t CO₂ eq (Table 9). Energy consumption, fertilizer production and soil emissions were the major sources, accounting for around 41, 31.6 and 26.7% of the total, respectively. If best recommended practices were implemented across the tea industry, the total GHG mitigation potential was 1666×10^4 t CO₂eq, amounting to around 57.9% of GHG emissions under conventional practice. The largest potential GHG mitigation action was the adoption of new energy sourcing for tea processing, namely

using biomass substituted for coal and electricity. Improved fertilizer management was another important GHG mitigation action (Table 9).

Table 9. Tea production in China: life cycle (cradle to factory gate after processing) GHG emission sources and mitigation potential.

Province	GHG Emission Sources (10^4 t CO ₂ eq)					Subtotal	Reduction Potential (10^4 t CO ₂ eq)			Subtotal
	Fertilizer	Pesticide	Diesel	Soil	Energy		Fertilizer	Soil	Energy	
Guizhou	124.6	0.48	2.51	96.8	144.2	368.6	47.3	16.1	130.6	194.0
Yunnan	121.9	0.51	2.72	95.1	170.7	390.9	40.6	7.7	154.6	202.9
Hubei	156.3	0.35	1.83	125.4	117.7	401.6	100.4	66.5	106.6	273.5
Sichuan	121.1	0.33	1.74	100.2	123.5	346.9	68.2	44.3	111.8	224.3
Fujian	63.8	0.33	1.72	45.9	194.0	305.8	10.9	0.0	175.7	186.6
Zhejiang	64.6	0.24	1.28	54.8	78.9	199.8	25.7	13.7	71.5	110.9
Anhui	46.3	0.20	1.05	39.0	59.1	145.6	14.9	5.3	53.5	73.7
Shanxi	21.2	0.14	0.72	23.3	39.2	84.6	0.6	0.1	35.5	36.3
Henan	27.8	0.16	0.84	24.9	29.5	83.2	2.8	0.0	26.8	29.6
Hunan	59.9	0.15	0.80	49.4	86.9	197.2	35.3	23.8	78.7	137.8
Jiangxi	39.0	0.10	0.51	29.1	28.2	96.9	23.1	12.6	25.6	61.3
Guangxi	18.2	0.08	0.44	17.3	30.0	66.0	5.2	3.4	27.2	35.7
Guangdong	13.6	0.06	0.31	17.1	41.9	73.0	4.2	7.3	37.9	49.4
Chongqing	7.2	0.05	0.25	6.4	16.3	30.3	0	0.0	14.8	14.8
Shandong	10.3	0.03	0.15	10.0	11.9	32.4	5.7	5.2	10.8	21.7
Jiangshu	11.4	0.04	0.22	9.9	6.2	27.8	4.6	2.8	5.6	13.0
Total	907	3.2	17.1	769	1178	2875	390	209	1067	1666

As for specific subsystems, the potential reduction in GHG emissions from the production of fertilizer inputs used in tea cultivation amounted to 390×10^4 ton CO₂eq, corresponding to 1.63 t CO₂ eq per ha or 1.46 kg CO₂ eq per kg of tea (Table 3). Compared to conventional fertilization practices in Table 2, this represents a GHG emissions reduction from farming inputs of more than 40%.

For the tea garden subsystem, with a decrease in fertilizers input, the N₂O emission from soil is also reduced. As shown in Table 4, if best recommended practices were implemented across the tea cultivation estate, the potential reduction in GHG emissions from soils amounted to 209×10^4 t CO₂eq, corresponding to 0.87 t CO₂eq per ha or 0.78 kg CO₂ eq per kg of tea. This represents a GHG emissions reduction from soil of more than 25%.

In the tea processing subsystem, coal, electricity, natural gas and biomass were used. However, if the same energy needs were met with biomass displacing coal, this action alone could potentially reduce GHG emissions in tea production by $1,067 \times 10^4$ t CO₂ eq (Table 9), and the GHG emissions reduction is more than 90% compared to using coal or electricity.

As far as the provinces are concerned, the emissions and respective mitigation potential differed between provinces (Table 9). The highest emissions (402×10^4 t CO₂ eq) and greatest GHG mitigation potential (274×10^4 t CO₂eq) was in Hubei province, followed by Yunnan (391×10^4 and 203×10^4 t CO₂eq), Guizhou (369×10^4 and 194×10^4 t CO₂ eq), Sichuan (347×10^4 and 224×10^4 t CO₂ eq), and Fujian (306×10^4 and 187×10^4 t CO₂ eq), respectively.

As for per ha picking area and per kg tea production, the total GHG emissions per ha tea garden under conventional management was 12.01 t CO₂eq, and the largest source was energy consumption (4.92 t CO₂ eq), followed by fertilization (3.79 t CO₂ eq) and soil emissions (3.21 t CO₂ eq) (Figure 3). If best recommended management practices were adopted, the potential GHG mitigation would be 6.96 t CO₂ eq ha⁻¹, a reduction of 58%. In relation to each kg of tea produced, the total emission was 10.76 kg CO₂ eq, which under best recommended management practices could potentially be reduced by 6.23 kg CO₂ eq per kg (Figure 4).

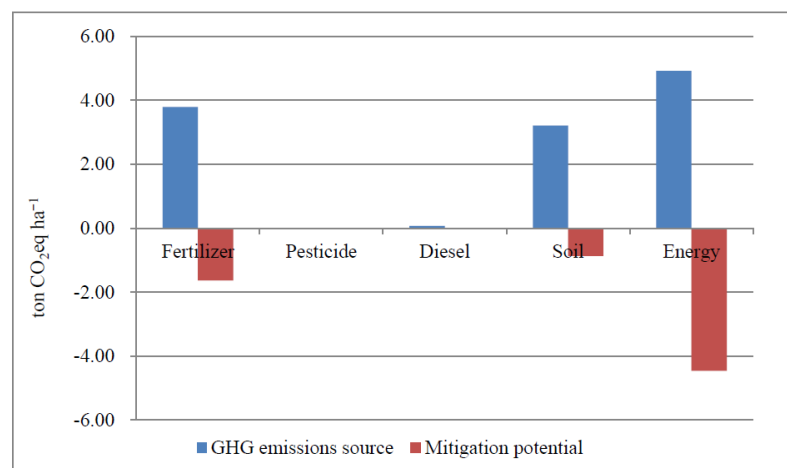


Figure 3. GHG emissions per ha of tea production in China (cultivation and processing) and the mitigation potential through adoption of best recommended management.

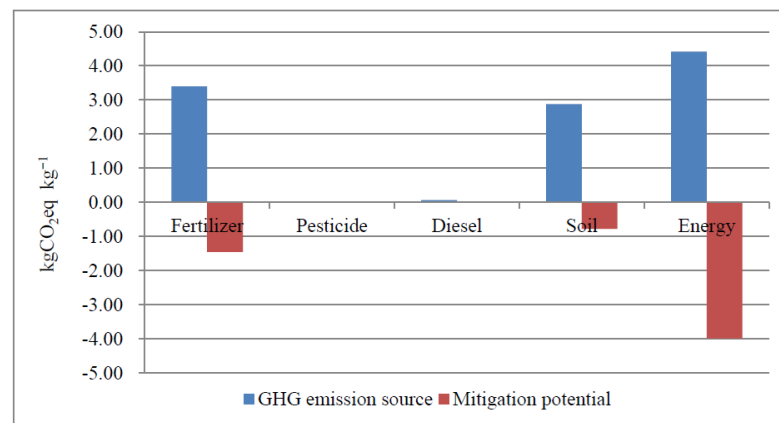


Figure 4. GHG emissions per kg of tea production in China (cultivation and processing) and the mitigation potential through adoption of best recommended management.

If C sink potential and GHG emissions reduction potential were combined, the benefit would be as high as 3802×10^4 t CO₂ eq, which is higher than GHG emissions of the tea industry. Thus, there would be a promising C pool if C sink and recommended management practices were taken into consideration (Figure 5).

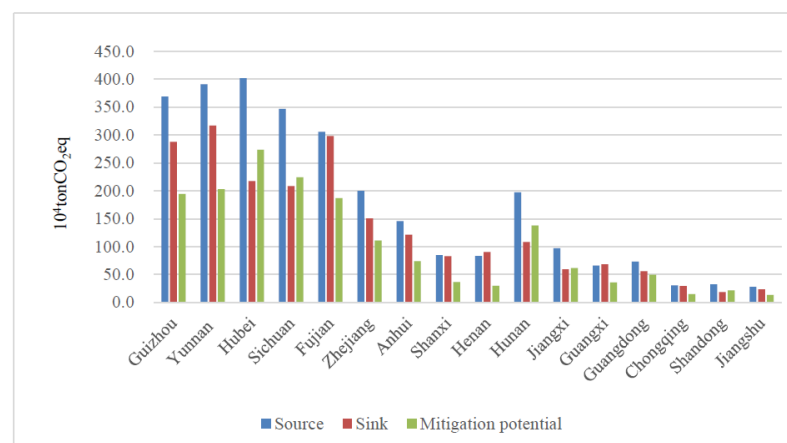


Figure 5. The main tea producing regions in China: GHG emissions, C sink, and potential for mitigation through adoption of best recommended management.

4. Discussion

4.1. GHG Emissions of the Tea Industry in China

This study has made a primary evaluation of GHG emissions and reduction potential for the tea industry in China in 2017. The total emissions (cradle to factory gate) for the 16 main tea producing provinces were 2875×10^4 t CO₂eq. This equates to 12.01 t CO₂ eq per ha of production area and 10.76 kg CO₂ eq per kg of processed tea. In China, the majority of studies examining GHG emissions in the agricultural sector have focused on staple food crops, such as rice, maize and wheat [53–57]. Studies relating to cash crops, such as tea, vegetables, and fruits, have been less common, despite the increasing economic importance of these crops and their environmental impacts [34,50,58,59]. The tea industry has been shown to be a relevant source of GHG emissions [41–43,48]. A national-scale assessment of GHG emissions in this industry is therefore important to guide strategic GHG mitigation efforts, especially at a time when in some areas, croplands traditionally used for cereal production are being converted into tea plantations and the tea processing sector is growing [60].

Estimates of the GHG emissions associated with tea production vary widely (Table 10), reflecting differences in production practices and efficiencies in specific regions, as well as differences in the modeling approaches that have been used. For example, Cichorowski et al. [14] assessed tea production in India, including the cultivation, harvesting, transport, use and waste disposal stages and reported GHG emissions ranging from around 7 to over 25 kg CO₂ eq per kg of Darjeeling tea. In contrast, Khanali et al. [16] assessed only the tea processing stage. In addition, studies are inconsistent in their modeling of GHG emissions from agricultural soils, which, as shown in this study, make an important contribution of total GHG emissions over the life cycle. Therefore, it is difficult to make direct comparisons among individual case studies.

Table 10. Survey of GHG emissions related to tea production.

Region	Boundary	Functional Unit	Carbon Emission	Reference
India	Cradle-to-grave	1.75g tea + 250 mL water	19–170 g CO ₂ eq	[15]
India	Cradle-to-factory gate	1kg Darjeeling tea	7.1–25.3 kg CO ₂ eq	[14]
India	Cradle-to-grave	8 g organic tea + 1L water	0.15 kgCO ₂ eq	[14]
Iran	Cradle-to-tea garden gate	1 t fresh tea	442 kg CO ₂ eq	[17]
Iran	Cradle-to-grave	1 kg Guilan tea	2.35–5.91 CO ₂ eq	[18]
Iran	Factory gate-to-factory gate	1 t dry tea	1319–1339 kg CO ₂ eq	[16]
Sri Lanka	Harvesting-to-factory gate	1 t tea	514–603 kg CO ₂ eq	[20]
Sri Lanka	Cradle-to-grave	1 kg tea	32 kg CO ₂ eq	[19]
Malawi	Factory gate-to-factory gate	1 kg tea	4.32 kg CO ₂ eq	[21]
Turkey	Cradle-to-supermarket gate	1 t tea	1730 kg CO ₂ eq	[22]
Turkey	Cradle-to-supermarket gate	1 t organic tea	1500 kg CO ₂ eq	[22]
Kenyan	Cradle-to-grave	1 kg tea	12 kg CO ₂ eq	[23]
China	Cradle-to-supermarket gate	1kg organic tea	4.5–19.9 kgCO ₂ eq	[49]
China	Cradle-to-factory gate	1 kg tea	10.76 CO ₂ eq	This study

4.2. Carbon Sink of the Tea Plantation Ecosystem

In the present study, the value of C sink amounted to $2,136 \times 10^4$ t CO₂, which could offset 74.3% of total C sources. This conclusion was based on the data reported by Li et al. [24] and Li [52], describing the carbon sink of China's tea plantation ecosystem. Li [52] assessed 563 biomass and 255 soil samples from 12 provinces which are the main tea producing regions (5 to 50 years old) in China. Compared to economic profitability and GHG emissions [18,19,23,34,61], relatively few studies have focused on carbon sinks in tea gardens. In west Kenya, Kamau et al. [27] evaluated the total C stocks in 14–76-year-old tea plantations. In Sri Lanka, Wijeratne et al. [62] assessed the carbon sequestration potential of tea plantations as an option for mitigating climate change and making a greener economy. As for India, Phukan et al. [63] and Pramanik and Phukan [26] estimated

CO₂ sequestration potential in tea gardens of the northeast, and the potential to mitigate global warming during tea cultivation, but these studies only made some measurements of CO₂ assimilation in tea and tea bushes, not considering the soil. In addition, Mishra and Sarkar [28] studied the relationship between total organic carbon and soil carbon pools under different land management systems, reporting useful potential of tea gardens as a C sequestering land use.

In China, although the function of tea gardens as a C sink has been noted [34,64,65], experimental research is relatively rare. Xiao et al. [66] estimated the carbon storage of different tree-tea agroforestry systems in Xishuangbanna, Yunnan province of southwest China. Sun et al. [67] also calculated the characteristics of carbon fluxes for tea garden ecosystems in the hills of western Lake Taihu Basin, China. Zhang et al. [25] analyzed the temporal evolution of carbon storage in Chinese tea plantations from 1950 to 2010. All these studies are focused on some specific locations and time spans, limiting their ability to support the development of priorities for strategic action at the national scale. Thus, C sink research of tea plantation ecosystems needs to be further strengthened from macro to microscale both in China and in other regions.

4.3. The Potential for GHG Emissions Mitigation

This study has shown that if best recommended management practices were adopted for tea production in China (namely reduced fertilizer inputs and biomass substituted for coal as an energy source), the GHG emissions could be reduced by 58%, or 1666×10^4 t CO₂ eq. In other words, the GHG emissions per ha tea production could be lowered from 12.01 to 5.05 ton CO₂ eq, and the corresponding values per kg of tea lowered from 10.76 and 4.53 kg CO₂ eq. In comparison, Kouchaki-Penchah et al. [17] identified GHG emissions reduction potential of around 19% for tea production in India by optimization of farming inputs. Cichorowski et al. [14] found that for Darjeeling tea production, the substitution of manure for chemical fertilizers could reduce GHG emissions from 9.6 to 3.3 kg CO₂ eq per kg of tea, a saving of almost two thirds. Munasinghe et al. [19] also identified the use of biomass for energy as a strategic priority for GHG emissions reduction in tea processing in Sri Lanka. Pelvan and Özilgen [22] emphasized organic production methods as a strategy to reduce GHG emissions in tea production, assuming yields remained equivalent to conventional production. In addition, machinery plays an important role in the tea industry, including in cultivation, transportation, and processing, etc. Therefore, using engines with higher efficiency is also an effective strategy to reduce GHG emission as well as reducing rolling resistance and decreasing the weight of vehicles [68,69]. In this study, we only considered fuel used in the process of transportation due to the limitation of data, and more researches are needed in future. However, in practice, this is not always the case [70,71]. In China, Xu et al. [49] estimated the carbon footprint of five Chinese organic tea products. The results showed that in the cultivation stage, the emissions were as low as 1.71 and 1.80 t CO₂ eq per ha. Therefore, the feasibility of wider adoption of organic production methods for tea cultivation in China should certainly be explored.

4.4. Critical Factor Analysis of the Tea Industry

Although China is the largest tea-producing country, GHG emissions both per unit planting area and per unit tea produced are higher than in some other regions (Table 10). Therefore, estimating the value of C sink of tea plantation and reducing GHG emissions should be a priority for China's tea industry. However, compared to other regions, it is evident that in China, inputs are high relative to the yields produced. In China, the average inputs of nitrogen (N), phosphate (P₂O₅) and potassium (K₂O) were 490, 170, and 199 kg per ha of cultivation, respectively (Table 1). In comparison, in Turkey, the corresponding inputs have been reported to be as low as 25, 30 and 15 kg per ha [22]. In Iran, inputs per ha of 355 kg for nitrogen, 66 kg for phosphate, and 351 kg for farmyard manure have been reported [17]. In India, for conventional tea production, inputs per ha of urea, muriate of potash, and rock phosphate have been reported at levels of 136, 100,

and 100 kg, respectively [14]. Conversely, in China, the average output is only 1,117 kg dry tea per ha of planting area (Table 1), and the yields in other regions, such as Iran, Turkey, Kenya and India, are reported to be much higher: 3,676, 3,182, 2,164 and 2,137 kg ha⁻¹, respectively [72]. Thus, increasing yield per unit of planting area while decreasing fertilizer use would appear to be very realistic in China.

In order to improve the yield and reduce the costs and environmental impacts of tea production in China, fertilizer use efficiency must be increased. However, in this regard, most attention to date has been upon nitrogen inputs, and less effort has been made to support efficient use of phosphate and potash [38,73–75] and the achievement of balanced fertilizer applications [34–36,76,77]. Tang et al. [36] has suggested that applications of N, P₂O₅ and K₂O should be in the proportions 0.5, 0.2 and 0.3. Following a 10-year field trial, Ji et al. [38] also recommended the use of inorganic and organic fertilizers at a ratio of 4:1 for tea production in China. However, the practical experience of Ni [32] and Ni et al. [34] found that tea producers in China rarely followed official recommendations based on field trials, and the quantity and ratio of fertilization were frequently unreasonable (Table 2). Thus, enhancing the level of uptake of best recommended management in terms of fertilization is a priority.

4.5. Limitations of the Study

In this study, GHG emissions, C sink potential, and reduction potential were quantified for the tea industry in China using best available data. In the case of planting areas and yields, detailed national statistics were used (see Section 2.1). In the case of C sinks, data were obtained from samples collected across the 12 major tea-producing provinces, which are considered reliable [24,52]. However, considering the importance of C sequestration in tea gardens, this could be expanded into a complete national dataset. With respect to fertilizer use, no complete and nationally consistent statistics are collected [59] and fertilizer use rates were based on data collected from field studies, which, although numerous, do not offer comprehensive coverage of all local practices. Secondly, there is a gap between planting area (304×10^4 ha) and picking area (239×10^4 ha), reflecting recent growth in the tea industry through the development of new tea gardens. In this study, the GHG emissions were evaluated only in relation to the area actually harvested. Thirdly, this study focused on the main life cycle stages of tea cultivation and processing in order to support environmental improvement in the tea industry. As such, the downstream life cycle stages of packing, use and disposal of spent tea leaves were excluded. However, these latter life cycle stages may also be important for GHG emissions mitigation. For example, when tea is packed into individual tea bags, the material use can be large and the GHG emissions from packaging can exceed the GHG emissions associated with tea cultivation and processing [19,22]. Moreover, Azapagic et al. [23] highlighted the GHG emissions associated with the boiling of water for tea consumption. The importance of such emissions depends upon the local source of energy and may vary substantially depending on the habits of users. For example, GHG emissions from tea preparation would be higher when unnecessarily large quantities of water are boiled. Thus, more works should be performed in the future.

5. Conclusions

Over the past ten years, an expansion in tea production in China has been encouraged in order to meet the increase of tea consumption as well as to provide greater economic opportunities for smallholder farmers. In 2018, the total area of tea plantation had reached 298×10^4 ha and the total production was 262×10^4 t, representing 60% of the global extent of tea plantations and 45% of global production. In light of the increasing importance of the Chinese tea industry, this study was the first national-scale assessment of GHG emissions and mitigation potential, based on the 16 major tea producing provinces.

The total GHG emissions from tea cultivation and processing were 2875×10^4 t CO₂ eq. Fertilizer production, soil emissions and energy consumption in tea processing accounted

for most of these emissions, representing 31.6%, 26.7%, and 41% of the total emissions, respectively. The amount of C sink of tea plantation ecosystem was 2136×10^4 t CO₂, which could offset 74.3% of GHG emission. If best recommended management practices were adopted for fertilizer application and if biomass was used as an alternative energy source, the GHG emissions reduction potential was 1666×10^4 t CO₂ eq, or 58% of total emissions from cradle to factory gate. Taken together, C sequestration and widespread adoption of best recommended management practices and energy procurement have the potential to render the tea industry an overall C sink as well as creating wealth and employment.

Almost two thirds of GHG emissions associated with tea production and processing were in five provinces: Hubei, Yunnan, Guizhou, Sichuan and Fujian. These five provinces, as well as Zhejiang, Anhui, and Hunan had the greatest C sink and GHG emissions reduction potential. As such, programs to increase the uptake of best recommended management practices should be directed towards these regions as the highest priority. In each of these eight provinces, the GHG emissions reduction potential exceeded 100×10^4 t CO₂ eq.

GHG emissions were also quantified per ha of picking area (12.01 t CO₂ eq) and per kg of processed tea (10.76 kg CO₂ eq). If considering the C sink of tea plantation, corresponding values would decrease to 3.08 t CO₂ eq and 2.76 kg CO₂, respectively. The adoption of best recommended practices in fertilizer use and the use of biomass instead of coal for energy in tea processing had the potential to reduce GHG emissions to 5.05 ton CO₂ eq per ha and 4.53 kg CO₂ eq per kg, respectively. In comparison with tea production and processing in other regions of the world, GHG emissions in China appeared high, and the potential for substantial GHG emissions reduction by the adoption of improved practices seems very realistic. The scale of the Chinese tea industry means that efforts to reduce GHG emissions can make a small, yet meaningful, contribution to China's climate action.

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