

Spatiotemporal Evolution and Features of Net Carbon Sink of Farmland Vegetation in Chongqing, China

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<https://doi.org/10.18280/ijstdp.150212>

ABSTRACT

Received: 17 June 2019

Accepted: 2 January 2020

Keywords:

Chongqing, farmland vegetation, net carbon sink (NCS), net carbon sink strength (NCSS), carbon absorption, carbon emissions

To promote sustainable development of agriculture, it is critical to reduce carbon sources and increase carbon sinks in farmland ecosystem by rationalizing the measures of agricultural management. This calls for scientific evaluation of net carbon sink (NCS) and its spatiotemporal evolution of farmland vegetation in a region. Taking 38 districts/counties of Chongqing, China as objects, this paper estimates the farmland vegetation NCS of Chongqing, based on statistics of crop yields and farmland inputs in 2000-2017. Then, geographical techniques were employed to analyze the features, regional difference and spatial evolution of NCS in Chongqing and its districts/counties. The main results are as follows: (1) From 2000 to 2017, the NCS and NCS strength (NCSS) of farmland vegetation in Chongqing both increased with fluctuations. The carbon sink, carbon emissions and carbon absorption increased across the board. The evolution of farmland vegetation can be divided into a wavy decline phase from 2000 to 2006, and a gradual increase phase from 2006 to 2017. (2) The source/sink structure of farmland vegetation in Chongqing remained stable in 2000-2017. The main sources are pesticide and tillage, and the main sinks are corn, rice, vegetables and oil crops. (3) In term of space, the farmland vegetation NCS and its center of gravity concentrated in the west zone and northeast zone. In general, the farmland vegetation of Chongqing boasts a strong carbon sink function; the west zone and northeast zone have the highest farmland vegetation NCSs; the west zone is the demonstration region of NCSS improvement.

1. INTRODUCTION

The carbon balance of the ecosystem has continued impacts on the environment [1], society and economy [2]. Low-carbon development is the only path towards a resource-saving and environment-friendly society [3]. As an important part of terrestrial ecosystem, the farmland ecosystem provides a huge carbon pool [4]. Agriculture can both emit and absorb carbon dioxide (CO₂) [5], whereas industry is a pure emitter [6]. Agricultural soil acts either a carbon sink or carbon source, which slows down or speeds up climate change [7]. On the one hand, farmland vegetation absorbs large amounts of CO₂ through photosynthesis and stores them in crops; on the other hand, the carbon is returned to the soil by straw mulching.

From 1900 to 2009, the crops in China absorbed a total amount of 525.6-676.13 total graphitic carbon (TgC), revealing the carbon-sink function of farmland vegetation [8]. To promote sustainable development, it is important to design and implement a reasonable system of carbon reduction policies. Such a system requires scientific measurement of the following indices of farmland vegetation: carbon absorption, carbon emissions, net carbon sink (NCS), and net carbon sink strength (NCSS) of farmland vegetation [9].

Foreign scholars have paid more attention to carbon pools of forest [10-12] than carbon sources/sinks in agricultural or farmland system. But the latter is arousing a growing interest in the academic circle. The relevant studies either focus on macro levels like country level [13, 14] and provincial level,

or target micro issues like soil carbon [15, 16]. For example, Kay et al. [17] held that agroforestry creates carbon sinks while enhancing the environment in agricultural landscapes. Focusing on Brazil, Russia, India, China and South Africa (BRICS), Balsalobre-Lorente et al. [18] demonstrated that agricultural activities induce carbon emissions, which in turn suppresses economic growth. Lv et al. [19] found the inter-annual changes in the interaction between grazing and warming. Taking the Lower Fraser Valley, Canada for example, Rallings et al. [20] suggested that the versatility of agricultural landscapes promotes agricultural carbon sinks. Jat, et al. [21] proved through experiments that, to protect soil aggregates, intensive management must adapt to local conditions, and advocated conservation agricultural practices, such as zero tillage, crop residue management and proper rotation. Based on evidences from Germany, Vos et al. [22] demonstrated that agronomic management can increase the carbon sink capacity of soil surface. Funes et al. [23] discovered that the organic carbon stock of surface soil is mainly influenced by climate, soil texture, and agricultural variables, while that of bottom soil is mainly affected by soil texture, clay content, soil type and bedrock depth. Hertwich and Peters [24] calculated the carbon footprint of Luxemburg and 72 other countries, using the multi-regional input-output (MIRO) model. Robertson et al. [25] recognized that the agricultural emissions of CO₂, nitrous oxide (N₂O) and methane (CH₄) contribute greatly to global greenhouse gases (GHGs).

Chinese scholars have mainly studied the carbon footprint of farmland soil and farmland ecology, but did not probe deep into the changes of net carbon sink in farmland vegetation [26]. Meanwhile, much research has been done on the effectiveness of agricultural carbon emissions [27], the development of low-carbon agriculture, and low-carbon agricultural production. However, there is little report on the district/county level.

To make up for the gap, this paper attempts to describe and analyze the changes in NCS of agriculture on the district/county level in an accurate, clear and detailed manner. For this purpose, the spatial scale was further refined, and spatial analysis instrument was adopted to systematically measure the spatiotemporal distribution of district/county-level agricultural NCS in Chongqing, China.

Firstly, the authors discussed about the estimation of the NCS of farmland vegetation, and estimated the NCS of farmland vegetation of Chongqing and its districts/counties between 2011 and 2017. Then, the time variation in district/county-level NCS of farmland vegetation was illustrated and examined based on time series and spatial method, aiming to disclose the law of spatiotemporal evolution of farmland vegetation NCS in Chongqing

2. STUDY AREA AND DATA SOURCES

2.1 Study area

Located in the middle reaches of the Yangtze River, Chongqing (N: 28°10'-32°13'; E: 105°11'-110°11') is a mountainous city of southwestern China. The altitude of the terrain gradually rises from the west to the east. The subtropical monsoon climate brings lots of precipitation.

Covering an area of 8.24×104km², Chongqing has a total of 38 districts/counties. Among them, 37 districts/counties are partially engaged in agriculture, and only Yuzhong District is fully urbanized. The districts/counties differ greatly in economic level. The urbanized district serves as a driving engine for the many rural districts/counties

Chongqing has a long history of agriculture, which involves a large portion of its population. The main crops include rice, wheat, rapeseed, sugar cane, fruits and vegetables. Besides agriculture, forestry, animal husbandry and fishery are all highly developed.

2.2 Data sources

The 38 districts/counties of Chongqing were taken as the research objects. The research data were mostly collected from *Chongqing Statistical Yearbooks* 2011-2018, the statistical data of the districts/counties, and the vector map of Chongqing urban planning. The collected data cover the carbon sink indices of farmland vegetation in 2000-2018 (e.g. the yield and planting area of 12 crops), and the agricultural production conditions (e.g. pesticide consumption, fertilizer consumption and sown area) that affect carbon emissions.

3. METHODOLOGY

According to United Nations Framework Convention on Climate Change (UNFCCC), source refers to any process or activity which releases a GHG (e.g. CO₂), an aerosol or a precursor of a GHG into the atmosphere; sink means

any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere.

On this basis, the difference between carbon sink and carbon source can be defined as the net carbon sink (NCS), a metric of the gap between the absolute values of carbon sink and carbon source.

According to the types of relevant carbon sinks and sources, agricultural production activities can be divided into two broad categories, namely, carbon emissions activities and carbon absorption activities. The former mainly includes ordinary production, irrigation, soil decomposition, livestock and poultry breeding, and straw burning. The latter consists of biomass, dead organic matter, and soil absorption.

In this research, agricultural carbon sinks/sources specifically refer to the carbon emissions and absorption, which take place in the agricultural production related to farmland vegetation.

3.1 NCS estimation

This paper defines the NCS of farmland vegetation as the difference between the carbon absorption and carbon emissions in crop growth period [6]. The carbon absorption in crop growth period can be estimated from the yield, carbon absorption rate, water content, economic coefficient, and root-shoot ratio of the crop [28]. The carbon emissions in crop growth period can be derived from the carbon emissions on different paths in agricultural production activities, namely, tilling machines, fertilizers, and pesticides [1].

The NCS can be estimated by the following formula:

$$C_T = \sum C_d = \sum [Q_i \times C_i \times (1 - W_i) \times (1 + R_i)] \div H_i \quad (1)$$

where, C_i is the total carbon absorption of regional crops (t); i is the serial number of crops; C_d is the carbon absorption of a crop (t); Q_i is the yield of crop i (t); C_i is the ratio of C_d to C_i (%); W_i , R_i and H_i are the water content, root-shoot ratio and economic coefficient of crop i , respectively (%).

This paper selects 12 main crops from Chongqing to estimate the carbon absorption. The relevant indices of the selected crops are listed in Table 1.

In farmland system, carbon absorption (sink) and emissions (source) occur at the same time. The carbon emissions of farmland vegetation can be converted from those of agricultural production activities. The carbon emissions coefficients used for the conversion are listed in Table 2.

Thus, the carbon emissions can be estimated by the following formula:

$$E_T = E_c + E_y + E_m + E_j + E_g + E_f + E_e \quad (2)$$

where, $E_c = G_c \times a$: E_c is the carbon emissions in fertilizer production and application; G_c is the consumption of fertilizers; $a = 0.8956 \text{ kg/kg}$;

$E_y = G_y \times b$: E_y is the carbon emissions in pesticide production and application; G_y is the consumption of pesticides; $b = 4.9341 \text{ kg/kg}$;

$E_m = G_m \times c$: G_m is the consumption of agricultural films; $c = 5.18 \text{ kg/kg}$;

$E_j = G_j \times d$: E_j is the indirect carbon emissions of the fossil fuels consumed to produce the electricity needed for irrigation; G_j is the area of effectively irrigated farmland; $d = 266.48 \text{ kg/hm}^2$;

$E_g = G_g \times e$: E_g is the direct and indirect carbon emissions of the electricity consumed by agricultural machinery; G_g is the diesel consumption of agricultural machinery; $e = 0.5927 \text{ kg/kg}$.

$E_f = G_f \times h$: E_f is the carbon emissions induced as the organic carbon pool of the soil is damaged by tillage; G_f is the sown area of crops; $h = 312.6 \text{ kg/hm}^2$.

$E_e = (S_e \times d) + (W_e \times f)$: E_e is the direct and indirect carbon emissions of the diesel consumed by agricultural machinery; S_e is the planting area of crops (hm^2); W_e is the total power of agricultural machinery; $d = 16.47 \text{ kg/hm}^2$; f is the sown area of crops $= 0.18 \text{ kg/kW}$; $h = 312.6 \text{ kg/hm}^2$.

On this basis, the NCS, denoted as C_{net} , can be estimated by:

$$C_{ent} = C_r - E_t \quad (3)$$

where, C_t and E_t are the carbon absorption and emissions of farmland vegetation, respectively.

Next, the NCSS, denoted as C_q , can be estimated by:

$$C_q = C_{ent} \div S_g \quad (4)$$

where, C_q is the NCSS, a.k.a. the carbon sink per unit of sown area (t/hm^2); S_g is the sown area of crops (hm^2).

3.2 Analysis of spatial evolution

The ArcGIS was adopted to identify the spatial distribution features of district/county-level farmland vegetation NCS in Chongqing. The spatial distributions of 2000, 2006 and 2008 were selected for comparison, with the aim to disclose the regional features of agriculture and guide the agricultural development in each district/county.

The moving center of gravity model was introduced to study the spatial evolution of farmland vegetation NCS in Chongqing. The spatial coordinates of the center of gravity of each object can be computed by:

$$\begin{aligned} X &= \frac{\sum P_u x_u}{\sum P_u} \\ Y &= \frac{\sum P_u y_u}{\sum P_u} \end{aligned} \quad (5)$$

where, X and Y are the longitude and latitude of the center of farmland vegetation NCS in Chongqing; P_u , x_u and y_u are the NCS, longitude and latitude of district/county u , respectively.

Then, the moving distance of the center from year u to year v , denoted as D_{u-v} , can be calculated by:

$$D_{u-v} = R \times \sqrt{(X_v - X_u)^2 + (Y_v - Y_u)^2} \quad (6)$$

where, (X_v, Y_v) and (X_u, Y_u) are the coordinates of the center of farmland vegetation NCS in year u and year v , respectively; $R = 111.11$ is the coefficient to convert geographical coordinates into planar coordinates (km).

Table 1. The main indices of the selected crops

Name	Carbon absorption rate	Water content	Economic coefficient	Root-shoot ratio
Rice	0.414	0.12	0.450	0.6000
Wheat	0.485	0.12	0.400	0.3933
Corn	0.471	0.13	0.400	0.1558
Sorghum	0.450	0.12	0.350	0.1393
Beans	0.450	0.13	0.340	0.1292
Tuber crops	0.423	0.70	0.700	0.1750
Oil crops	0.450	0.10	0.250	0.0400
Fiber crops	0.450	0.15	0.3560	0.2915
Sugar crops	0.450	0.50	0.500	0.4151
Tobacco leaf	0.450	0.85	0.550	0.3175
Vegetables	0.450	0.90	0.600	-
Fruits	0.450	0.90	0.700	-

Note: The parameters were extracted from Tian et al. [27]; the root-shoot ratio of soybean was taken as that of beans; the root-shoot ratio of tuber crops was obtained from Miao et al. [29]; the parameters of rapeseeds were taken as those of oil crops; the parameters of sugar cane were taken as those of sugar crops; the parameters of melons and strawberry were taken as those of fruits; the root-shoot ratios of vegetables and fruits were not considered, due to the complex varieties of these plants.

Table 2. Carbon emissions coefficients of agricultural production activities

Sources	Carbon emissions coefficient	Unit	References
Fertilizers	0.8956	kg/kg	Tian Yun et al.
Pesticides	4.9341	kg/kg	Tian Yun et al.
Agricultural films	5.18	kg/kg	Tian Yun et al.
Irrigation	266.48	kg/hm ²	West et al.
Diesel	0.5927	kg/kg	Tian Yun et al.
Tillage	312.6	kg/hm ²	Wu Fenlin et al.
Agricultural machinery	16.47	kg/hm ²	
	0.18	kg/kW	

4. RESULTS AND ANALYSIS

4.1 Overall features of NCS

According to the above estimation methods and indices, the carbon absorption, carbon emissions and NCS of farmland

vegetation in Chongqing between 2000 and 2017 were calculated, and compiled into a number of figures (Figures 1-2) and a table (Table 3).

As shown in Figure 1, the NCS and NCSS of farmland vegetation in Chongqing increased between 2000 and 2017 with some fluctuations. The growths were prominent: 33.23%

for NCS, and 41.84% for NCSS. From 2000 to 2017, the NCS of farmland vegetation rose from 3.772 to 5.026 million t, while the NCSS increased from 1.50 to 2.12t/hm². Both NCS and NCSS reached the peak values in 2017. The minimum NCS was 3.285 million t in 2006, and the minimum NCSS was 1.33t/hm² in 2001.

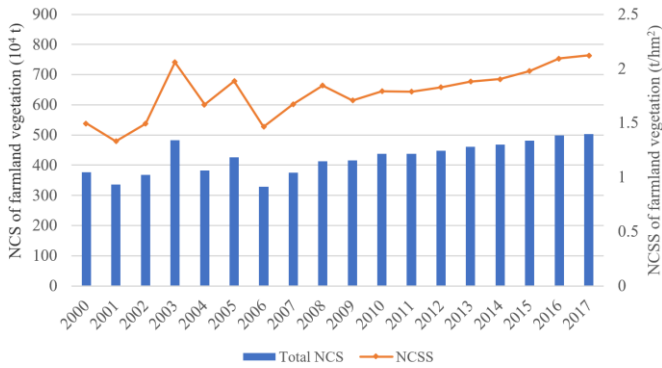


Figure 1. Variations in NCS and NCSS of farmland vegetation in Chongqing (2000-2017)

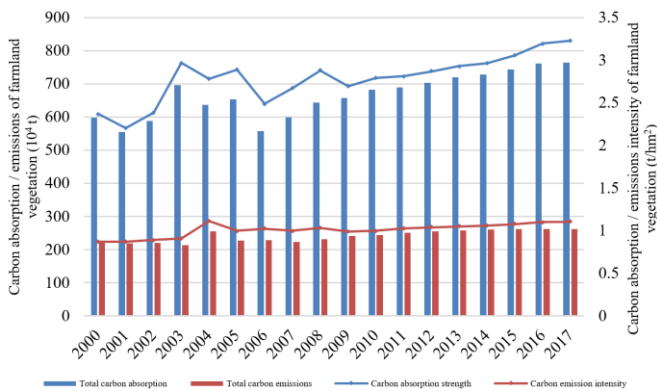


Figure 2. Variations in carbon absorption and emissions of farmland vegetation in Chongqing (2000-2017)

Overall, the NCS of farmland vegetation evolved in two phases: wavy decline and gradual increase. The first phase

lasts from 2000 to 2006, where the NCS of farmland vegetation fluctuated several times. The second phase starts from 2006, where the NCS gradually rose from the lowest level.

As shown in Figure 2, the carbon emissions and carbon emissions strength of farmland vegetation in Chongqing both increased slowly. From 2000 to 2017, the total carbon emissions of farmland vegetation grew by 18.89% from 2.2019 to 2.6176 million t, while the carbon emissions strength surged by 26.57% from 0.87 to 1.10t/hm². The maximal and minimal carbon emissions appeared as 2.6208 million t in 2016 and 2.1375 million t in 2003, respectively; the maximum and minimal carbon emission strengths were observed as 1.11t/hm² in 2014 and 0.87t/hm² in 2001, respectively.

The carbon absorption and carbon absorption strength of farmland vegetation in Chongqing also exhibited a continuous growth. From 2000 to 2017, the total carbon absorption of farmland vegetation increased by 27.95% from 5.9744 to the peak of 7.6440 million t, while the carbon absorption strength soared by 36.21% from 2.36 to the peak of 3.23 t/hm². The minimal carbon absorption was found in 2001 (5.5456 million t). Starting from 2006, the trend of carbon emissions strength became increasingly similar to that of carbon absorption strength of farmland vegetation.

4.2 Sink/source structure

Table 3 lists the sink/source structure of farmland vegetation in Chongqing (2000-2017). It can be seen that the sink structure remained stable from 2000 to 2017. In terms of perennial medians, corn, rice, vegetables and oil crops account for 31%, 25%, 13% and 10% of the sink structure, respectively, in the said period. Together, the four crops take up nearly 80% of the sink structure, and the proportion was gradually rising.

The source structure was also rather stable in the said period. In terms of perennial medians, fertilizer and tillage both contributed greatly to carbon emissions, taking up 33% and 41% of the source structure, respectively. The combined contribution of the two variables surpassed 74%, and slowly decreased from then on.

Table 3. The sink/source structure of farmland vegetation in Chongqing (2000-2017)

Year	Sinks				Sources	
	Corn	Rice	Vegetables	Oil crops	Fertilizers	Tillage
2000	28%	28%	10%	8%	29%	49%
2001	30%	27%	11%	8%	30%	48%
2002	30%	27%	11%	9%	30%	47%
2003	26%	37%	9%	9%	30%	46%
2004	31%	26%	10%	10%	27%	51%
2005	31%	26%	10%	10%	31%	45%
2006	32%	22%	12%	11%	31%	44%
2007	34%	27%	11%	8%	34%	41%
2008	33%	27%	12%	9%	34%	41%
2009	32%	25%	14%	10%	34%	41%
2010	32%	25%	15%	10%	34%	41%
2011	32%	23%	16%	11%	34%	40%
2012	32%	23%	17%	11%	34%	40%
2013	31%	23%	17%	11%	34%	40%
2014	30%	22%	18%	12%	33%	40%
2015	30%	22%	18%	13%	33%	40%
2016	30%	22%	19%	13%	33%	41%
2017	30%	22%	20%	14%	33%	41%
Median	31%	25%	13%	10	33%	41%

4.3 Spatial distribution of NCS

This subsection investigates the carbon emissions, carbon absorption and farmland vegetation NCS of each district/county in Chongqing, laying the basis for rational measures of carbon emissions. The Yuzhong District was not considered in the investigation. The carbon emissions, carbon absorption and farmland vegetation NCS of the remaining 37 districts/counties in 2000-2017 were measured. The NCS and NCSS data of 2000, 2016 and 2017 were imported to ArcGIS to plot the spatial evolution map of the farmland vegetation NCS in Chongqing. The map was used to analyze how the farmland vegetation NCS evolved in time and space.

The 38 districts/counties of Chongqing were divided into four economic zones: main city zone, west zone, northeast zone, southeast zone. The main city zone covers Yuzhong District, Dadukou District, Jiangbei District, Shapingba District, Jiulongpo District, Nan'an District, Beibei District, Yubei District, and Banan District; the west zone covers Fuling District, Changshou District, Jiangjin District, Hechuan District, Yongchuan District, Nanchuan District, Qijiang District, Dazu District, Bishan District, Tongliang District, Taongnan District and Rongchang District; the northeast zone covers Wanzhou District, Kaizhou District, Liangping District, Chengkou County, Fengdu County, Dianjiang County, Zhongxian County, Yunyang County, Fengjie County, Wushan County, and Wuxi County; the southeast zone covers Qianjiang District, Wulong District, Shizhu County, Xiushan County, Liyang County, and Pengshui County.

4.3.1 Spatial features of NCS

In terms of space (Figure 3), there was obvious regional difference of farmland vegetation NCS in Chongqing. In 2000, the high NCS mainly existed in most districts/counties of west zone and a few districts/counties of northeast zone. In 2006, fewer districts/counties of west zone had high NCS. In 2017, northeast zone had more high-NCS districts/counties than other zones. The west and northeast zones were the major contributors of NCS in Chongqing. In 2017, 47.32% of carbon absorption in field vegetation of Chongqing occurred in the west zone, and 33.74% took place in northeast zone. Together, the two zones accounted for 81.06% of carbon absorption in field vegetation of Chongqing. By contrast, the proportions of southeast zone and main city zone were merely 0.14% and 0.53%, respectively. In addition, the top 16 districts/counties in farmland vegetation NCS all come from west and northeast zones.

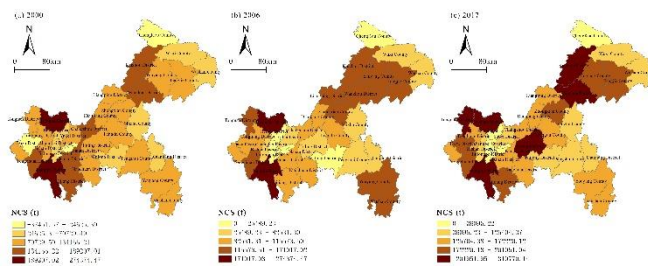


Figure 3. Spatial evolution of farmland vegetation NCS in Chongqing

In 2017, the top ten districts/counties in farmland vegetation NCS consisted of 5 districts/counties from west zone and five from northeast zone. The top district/county was Hechuan District (31,980,000 t), followed by Tongnan District

(31,350,000 t), Jiangjin District (30,280,000 t) and Fuling District (27,550,000 t). Nan'an District (9,000 t) came at the bottom of the ranking of farmland vegetation NCS, behind Jiangbei District (9,200 t), Dadukou District (2,400 t), and Shapingba District (6,500 t). The NCS of the top district/county (Hechuan District) was 349.58 times of that of the bottom district/county (Nan'an District).

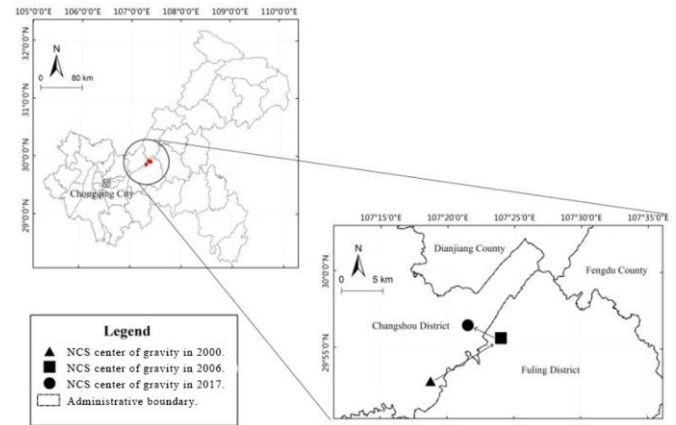


Figure 4. Shift in NCS center of gravity in Chongqing

As shown in Figure 4, the NCS center of gravity shifted from Changshou District in 2000, to Peiling District in 2006 and returned to Changshou District in 2017. The center of gravity always fell within the west zone. Therefore, the west zone is the focal point of farmland vegetation NCS in Chongqing. Over the 18 years, the center of gravity moved by 11.04km in 2000-2006, 4.83km in 2006-2017, and 8.50km in 2000-2017. In general, the moving distance for the center of gravity was relatively stable, with only a slight change, and the center of gravity remained in the west zone.

4.3.2 Spatial features of NCSS

In terms of space (Figure 5), there was also obvious regional difference of farmland vegetation NCSS in Chongqing. The four zones were ranked as west zone > northeast zone > southeast zone > main city zone by the NCSS.

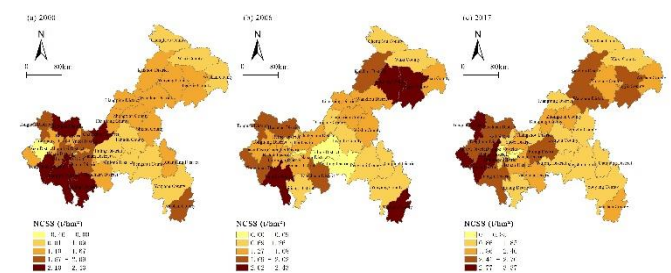


Figure 5. Spatial evolution of farmland vegetation NCSS in Chongqing

As shown in Figure 6, the top ten districts/counties in farmland vegetation NCSS in 2017 all belong to west and northeast zones. Tongnan District had the highest NCSS (3.37t/hectare), followed by Yongchuan District, Rongchang District, and Bishan District. Nan'an District had the lowest NCSS (0.29t/hectare), behind Jiangbei District (0.37t/hectare), Shapingba District (0.85t/hectare) and Pengshui County (1.16t/hectare). The highest value is 11.62 times of the lowest value.

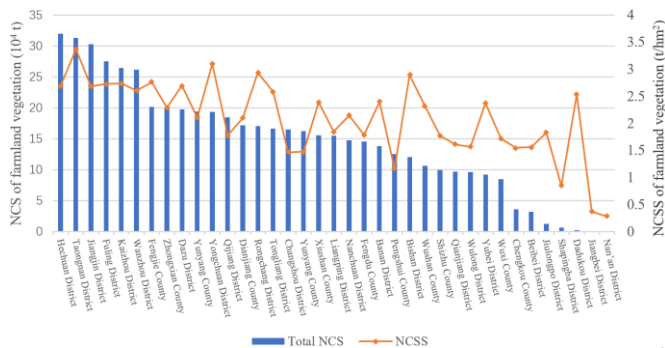


Figure 6. District/county-level NCSs and NCSSs of Chongqing in 2017

To sum up, Tongnan District, Hechuan District, Jiangjin District and Dazu County have relatively high NCSs, NCSSs and carbon sink levels of farmland vegetation. It can be seen that, in these districts/counties, agricultural production features a large scale and high carbon efficiency; the farmland ecosystem can purify the GHGs released by secondary and tertiary industries to a certain extent, which promotes the carbon balance in the ecosystem.

On the contrary, Nan'an District, Jiangbei District and Shapingba District had relatively low NCSs, NCSSs and carbon sink levels of farmland vegetation. These districts mainly belong to the main city zone. Besides pursuing economic growth, the main city zone should fully utilize farmland vegetation, increase carbon sink efficiency and promote carbon balance in urban ecosystem.

5. CONCLUSIONS

(1) From 2000 to 2017, farmland vegetation in Chongqing had strong carbon sink function, and witnessed a continuous increase in carbon absorption (27.95%) and NCS (33.23%). In terms of NCS, southeast zone ranked the first, followed in turn by northeast zone, west zone and main city zone.

The farmland vegetation NCSS exhibited a growing trend: southeast zone remained on the top, followed in turn by northeast zone, west zone and main city zone. The minimal carbon absorption and minimal NCS in farmland vegetation appeared in 2001 and 2006, respectively, for the crop failure under dry weather.

Based on the lowest point of 2006, the evolution of farmland vegetation NCS can be divided into two phases: wavy decline from 2000 to 2006 and gradual increase from 2006 to 2017. The low carbon sink in 2006 is attributable to a severe drought. Except for that year, the NCSS remained high in west zone, thanks to the construction of Chongqing metropolitan area; the northeast zone, with better natural conditions than southeast zone, saw a continuous growth in farmland vegetation NCS under the policies on poverty alleviation.

(2) From 2011 to 2017, the source/sink structure of farmland vegetation remained stable in Chongqing. The main sources are pesticide and tillage, which account for 33% and 41% of total carbon emissions, respectively; the main sinks are corn, rice, vegetables and oil crops, which occupy 31%, 25%, 13% and 10% of total carbon absorption, respectively.

The carbon absorption of vegetables increased dramatically by 149% from 586,399.43t in 2000 to 1,460,382.53t in 2007, while that of oil crops also surged by 107% from 482,981.46t in 2000 to 1,000,956.27t in 2017. Meanwhile, vegetables

accounted for 10% of the total carbon absorption of farmland vegetation in 2000, which rose by 104.71% to 20% in 2017; oil crops accounted for 8% of the total carbon absorption of farmland vegetation in 2000, which rose by 9.91% to 14% in 2017. The main reason lies in the low economic benefits of grain crops and high economic coefficient of vegetables, because it is difficult to manage the fragmented lands intensively in mountainous regions of Chongqing; many farmers have shifted from food crops to cash crops like vegetables and oil crops, resulting in a continuous increase in the output of cash crops.

With socioeconomic development, urbanization has encroached some farmlands. In 2017, the farmland area in Chongqing dropped by 6.07% from the level of 2000. As a result, rice, the main food crop in Chongqing, decreased by 11.16% in sown area, 2.95% in yield and carbon absorption, and 24.15% (from 28.48% to 21.6%) in contribution to carbon absorption of farmland vegetation. By contrast, corn can adapt well to the local climate and terrain: the yield was growing slowly and steadily, the carbon absorption rose from 1,697,154.82t in 2000 to 2,287,681.30t in 2017, and the contribution to carbon absorption of farmland vegetation climbed from 28.41% to 30.14%.

(3) Generally speaking, farmland vegetation in Chongqing has absorbed much more carbon than the amount it emitted. This means farmland vegetation boasts powerful carbon sink function, and the farmland system enjoys high carbon efficiency. Both of them ease the environmental pressure from carbon emissions.

From 2000 to 2017, the farmland vegetation NCS of Chongqing mainly concentrated in the west zone and northeast zone; the NCS center of gravity shifted from the west zone to the northeast zone, and recently moved to the west zone.

The farmland vegetation NCSS in west zone was relatively high, thanks to the excellent location, high agricultural input, and advantageous social economy. The NCSS in northeast zone exhibited a growing trend. The NCSS in southeast zone remained stable on a low level, for the terrain of Chongqing is higher in the east and lower in the west.

To fully utilize the carbon sink function of farmland vegetation, the above zones must attach importance to ecological agriculture, protect farmland and modernize agriculture in future [16, 17]. In the west zone, modern urban agriculture is developing rapidly, as evidenced by the growing investment in agriculture. Therefore, the farmland ecosystem in this zone has an ecological surplus, which is conducive to environment and ecology. However, the productivity and NCS are relatively low in the southeast zone, due to its relative poverty, mountainous landform and weak agriculture foundation.

(4) In Chongqing, farmland vegetation NCS and its center of gravity mainly lie in the west zone and northeast zone. In future, the two zones should focus on developing low-carbon industries and green agriculture. The government should guide farmland protection, giving fully play to the carbon sink function of farmland vegetation.

First, the government should improve agricultural technology and management, and develop green agriculture, enhancing the carbon absorption capacity.

Second, the government should encourage farmland protection to reduce erosion and improve soil fertility. Possible measures include zero tillage, protective agriculture, irrigation, rotation and so on.

Third, the government should increase crop yields by

promoting good crop varieties. The southeast zone, as well as other zones with unfavorable landform, should elevate carbon sink function of farmland ecosystem through agroforestry.

Fourth, the government should strengthen land use management, evaluate organic carbon components in farmland soil, and improve the carbon management [24], thereby ensure carbon balance and ecological sustainability of farmland system.

(5) For the availability of data, the district/county-level NCS was only computed based on the main indices of source/sink structure. Many source/sink elements were not taken into account. The ignored elements may not affect the spatial distribution, but inevitably caused certain errors. The future research will collect even more data and try to increase the computing accuracy.

ACKNOWLEDGMENT

This paper is based on the Postdoctoral Research "Comparative study on the transformation and development of resource-exhausted cities in eastern and western China". Project supported by the Fundamental Research Funds for the Central Universities of Ministry of Education of China (Grant No. SWU1509447), Chongqing social science planning project (2019YBGL076), and Chongqing "University Innovation and Entrepreneurship Training Program" Project (S201910635049).

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