J. Geogr. Sci. 2020, 30(10): 1590-1602
DOI: https://doi.org/10.1007/s11442-020-1801-0

Patterns and trends in grain self-sufficiency on the Tibetan Plateau during 1985–2016

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Abstract: Capacity for grain self-sufficiency on the Tibetan Plateau (TP) is an important basis for ensuring social stability and regional sustainability. Thus, based on county-level statistical data for population, grain production and consumption, we analyzed patterns and trends in grain supply and demand at regional, provincial, and county levels on the TP between 1985 and 2016. We applied two indices to evaluate capacity for grain self-sufficiency and found that the regional average self-sufficiency rate increased quickly by 1.97%/a since 1989, reaching 173.03% on the plateau over the period between 2010 and 2016. This indicates that grain supply in this region is able to fully meet demand. In addition, all provinces apart from Xinjiang exhibited similar increasing trends, attaining grain self-sufficiency during 2010–2016. Furthermore, 59% of counties attained grain self-sufficiency over this period, mainly distributed in southern Tibet, in the Sichuan-Tibet junction area, and in eastern Qinghai Province. A number of gaps in grain supply and demand occurred within the headwater regions of the Yangtze and Yellow rivers as well as on the Qiangtang Plateau. Grain self-sufficiency significantly increased over the study period in 36% of counties, mainly distributed in the agricultural areas of southeastern Tibet and in eastern Qinghai. Across the whole plateau, capacity for grain self-sufficiency substantially increased between 1985 and 2016, although serious spatial imbalances remain.

Keywords: Tibetan Plateau; grain; county scale; self-sufficiency; spatiotemporal distribution

1 Introduction

Food security is an essential component of national security and social stability (Wang *et al*., 2015). It depends on not only improvement in grain production capacity but also changes in

Received: 2020-06-18 **Accepted:** 2020-08-06
Foundation: Strategic Priority Research Program of the Chinese Academy of Sciences, No.XDA20040301; National Natural Science Foundation of China, No.41771111; The Youth Innovation Promotion Association, Chinese Academy of Sciences, No.2018071; Fund for Excellent Young Talents in Institute of Geographic Sciences and Natural Resources Research, CAS, No.2016RC201; Hebei Natural Science Foundation, No.D2019205123; Research Fund of Hebei Normal University, No.L052018Z09
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regional demand (Xu *et al*., 2013). Although grain supply is approximately balanced at the moment across China, capacity for self-sufficiency varies with time and space (Nie *et al*., 2010). Due to continuous growth in demand for grain, there is an urgent need to scientifically evaluate the supply-demand balance and effectively coordinate regional structures in this respect to ensure food security and social stability (Fukase and Martin, 2016; Jin *et al*., 2016). The Tibetan Plateau (TP) is variously described as the 'Roof of the World', the 'Water Tower of Asia', and the 'Third Pole of the Earth'. It is also an important eco-security barrier and a basis of strategic resource reserve for China. Capacity for grain self-sufficiency on the TP is related to strategies on regional sustainable development (Xu *et al*., 2017). It is noteworthy that food was insecure on the TP for a long time because of a weak ability to respond to natural disasters (Qi *et al*., 2015). Ensuring food supply from this region has also placed significant pressure on agricultural resources and the environment (Cheng and Shen, 2000; Wen, 2000). It is therefore necessary to alleviate pressures on demand caused by population growth and imbalances in supply and demand by properly evaluating food security on the TP (Min *et al*., 2003; Duan *et al*., 2019). At the core of food security evaluation, analysis of spatiotemporal variations in grain supply and demand on the TP forms the basis of regional food security evaluation.

Significant differences in capacity for grain self-sufficiency on the TP have been reported at different spatiotemporal scales. At the regional scale, some previous work has shown that it has been difficult for total grain production on the TP to meet demand (Duan *et al*., 2019), while results reported at the provincial level indicate conversely that capacity for grain self-sufficiency could be achieved in Tibet (Gu, 2000; Liu *et al*., 2004). Grain yield in Qinghai Province is relatively low and sown area has slightly decreased (Su *et al.*, 2017). Studies on supply at various stages have shown that grain across Tibet has been self-sufficient since 1997 (Gu, 2000). According to the per capita grain consumption of residents reported in a sample survey, supply and demand across Tibet has been balanced since 2001 (Liu *et al*., 2004), and supply reached a level 1.5 times demand by 2010 (Gao *et al.*, 2017). Grain consumption in Qinghai and Tibet also steadily increased between 1985 and 2015 (Duan *et al*., 2019), while production in Tibet fluctuated but increased between 1985 and 2010 as a result of regulation of spatial strategy in cropland area, agricultural production conditions, and animal husbandry (Cheng and Min, 2002; Yang *et al*., 2015). Qinghai depended on imported grain between 1991 and 1996, indicating that per capita levels remained relatively low and that supply was insufficient (Shangguan, 1998). The degree of grain self-sufficiency in Tibet gradually increased between 1991 and 1998; it was clear that by 1997 demand for food had been met (Gu, 2000). At the same time, however, county level studies have revealed differences in the impact of per capita consumption levels on both cropland productivity and food security of Tibet (Wang *et al*., 2019). Inconsistent conclusions for grain self-sufficiency have therefore been reached because different standards for measuring this variable have been applied in previous studies. Patterns and trends in grain self-sufficiency on the TP remain contentious, especially spatiotemporal variations at the county level over recent decades.

Here, we studied grain supply and demand on the TP based on grain production, population, and per capita consumption data collected at the county level between 1985 and 2016. We distinguished variations in consumption within urban and rural areas at the county level

within each region. Spatiotemporal variations in capacity for grain self-sufficiency on the TP at regional, provincial, and county levels between 1985 and 2016 were evaluated systematically. Our studies can provide a foundation for building an eco-security barrier and a regulation of spatial strategy for regional agriculture and animal husbandry on the TP.

2 Data and methods

2.1 Study area

The TP includes 205 counties and is located in southwest China, including Qinghai and Tibet as well as some parts in Sichuan, Yunnan, Gansu, and Xinjiang provincial-level regions (Figure 1). The average elevation of the TP is more than 4,000 m. The TP experiences a typical plateau climate, significantly different from others at the same latitude, changing from warm and humid in the southeast to cold and dry in the northwest (Shen *et al*., 2019; Zheng *et al*., 2019). Vegetation types here also gradually change from forest to grassland and then to desert along a southeast-to-northwest transect. Grassland is the most widely distributed vegetation type, while shrubs are mainly distributed in the south (Shen *et al*., 2019). Available cropland area is small and concentrated in the region of 'the Yarlung Zangbo River and its two tributaries' and the Yellow River-Huangshui River Valley; these regions have relatively low altitude with abundant heat resources and the fertile soils (Zhang *et al*., 2019).

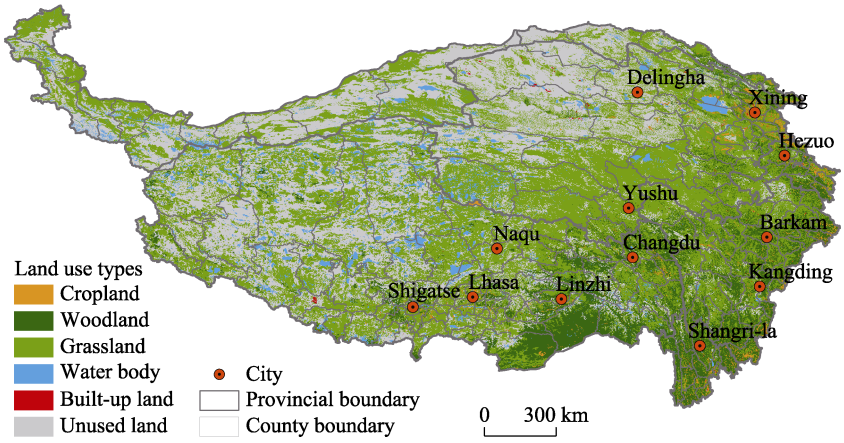

Figure 1 Distribution of land use types on the Tibetan Plateau

2.2 Data

2.2.1 Land use types

Land-use type data for 2015 were downloaded from the Resource and Environmental Science Data Center of Chinese Academy of Sciences (http://www.resdc.cn).

2.2.2 Grain supply and demand

Data on grain supply and demand, including production at provincial and county levels, as well as per capita annual grain consumption for urban and rural residents (1985–2016) were

extracted from the Qinghai Statistical Yearbook (1985–2017), the Tibet Statistical Yearbook (1993–2017), the Gansu Development Yearbook (1984–2017), the Yunnan Statistical Yearbook (1984–2017), the Xinjiang Statistical Yearbook (1989–2017), and the Sichuan Statistical Yearbook (1987–2017).

2.2.3 Population data

Provincial- and county-level population data, including resident populations at year-end as well as urban and rural resident population between 1985 and 2016, were extracted from the Qinghai Statistical Yearbook (1985–2017), the Tibet Statistical Yearbook (1993–2017), the Gansu Development Yearbook (1984–2017), the Yunnan Statistical Yearbook (1984–2017), the Xinjiang Statistical Yearbook (1989–2017), the Sichuan Statistical Yearbook (1987–2017), China Population Census Data by County, and the China Population and Employment Statistical Yearbook (1988–2017).

2.3 Methods

2.3.1 Grain consumption

Grain consumption was calculated as follows:

$$CA_k = CU_k + CR_k = PUA \times CUP_k + PRA \times CRP_k \quad (1)$$

where CA_k, CU_k, and CR_k denote the annual grain consumption of total, urban, and rural populations in the *kth* county, respectively; *PUA* and *PRA* denote the per capita annual grain consumption of urban and rural populations at the provincial level, respectively; CUP_k and CRP_k denote urban and rural populations in the *k*th county, respectively.

2.3.2 Indicators of grain self-sufficiency

The supply-demand gap as well as the self-sufficiency rate were used to assess the current situation and trends in grain self-sufficiency on the TP. The supply-demand gap was calculated as follows:

$$G_t = D_t - S_t \quad (2)$$

where G_t denotes the grain supply-demand gap in the *t*th year; D_t and S_t denote total grain demand (or consumption) and supply in the *t*th year, respectively. Thus, $G>0$ means that consumption exceeds supply, while $G<0$ denotes the reverse, and $G=0$ indicates that the two variables are in balance.

The self-sufficiency rate was calculated as follows:

$$d_t = (S_t / D_t) \times 100 \quad (3)$$

where d_t indicate the degree of grain self-sufficiency in the *t*th year (%). Thus, d_t >100% means that supply exceeds demand, while d_t <100% denotes the reverse, and d_t =100% indicates that the two variables are in balance.

2.3.3 Trend analysis

The slope of the supply-demand gap and self-sufficiency rate for grain on the TP were analyzed as follows:

$$d = q_0 + aN \quad (4)$$

$$G = b + kN \quad (5)$$

where d refers to grain self-sufficiency rate, q_0 is the intercept, and a is the average annual change of grain self-sufficiency. Similarly, G denotes the supply-demand gap, b is the intercept, k is the average change of grain supply-demand gap, and N denotes the year.

2.3.4 Supply and demand data processing in marginal counties

A total of 11 counties are not fully included within the scope of the TP; they are Yecheng, Minfeng, Yutian, Cele, Pishan, Hotan, Qiemo, Ruoqiang, Aktao, Minle, and Shandan. Supply and demand data for these counties were therefore processed by first calculating the proportion of cropland on the plateau in each case and then calculating the proportion of residential area. Grain production, consumption, self-sufficiency rate, and the supply-demand gap for marginal counties lacking settlements were then reported as non-residential areas and were not included subsequently. Finally, marginal counties encompassing residential areas were identified as Qiemo, Yutian, Minfeng, Minle, and Shandan counties. Grain production and consumption values for these areas were then calculated based on the proportion of cropland and built-up area in each case, respectively (Table 1).

Table 1 Revised methods for calculating grain supply and demand in marginal counties of the Tibetan Plateau

County	Adjustment in grain production (P_{all})	Adjustment in grain consumption (C_{all})
Minle	$P_{all} \times 0.005$	$C_{all} \times 0.002$
Shandan	$P_{all} \times 0.001$	$C_{all} \times 0.001$
Qiemo	$P_{all} \times 0.014$	$C_{all} \times 0.024$
Yutian	$P_{all} \times 0.006$	$C_{all} \times 0.017$
Minfeng	$P_{all} \times 0.042$	$C_{all} \times 0.033$

Notes: P_{all} and C_{all} denote total grain production and consumption in each county, respectively.

3 Results and analysis

3.1 Spatiotemporal variation in grain self-sufficiency across the whole TP

3.1.1 The current situation

Grain production generally meets local needs on the TP. Grain production on the TP is mainly distributed within the basins of 'the Yarlung Zangbo River and its two tributaries' as well as in the eastern part of Qinghai Lake. Between 2010 and 2016, average annual total grain production and consumption values for the TP were 558.12×10^4 t and 322.56×10^4 t, respectively, revealing that there was no supply-demand gap across the whole TP (Figure 2a). During this period, the self-sufficiency rate was 173.03% in the whole region (Figure 2a), and values for average annual total consumption in urban and rural areas were 47.50×10^4 t and 273.27×10^4 t, respectively, indicating that there was a big variance between urban and rural areas (Figure 2b).

3.1.2 Trends in grain self-sufficiency

Total grain production on the TP has maintained a relatively steady increase since 1989, with an average annual change of 5.70×10^4 t, especially since 2005 (Figure 2a). Overall grain consumption has slightly decreased over this time period, with an average annual decline of 0.51×10^4 t, most markedly after 2010. The decrease of per capita annual consumption in urban areas (1.79 kg/a) was higher than in rural areas (1.28 kg/a) (Figure 2b). Similarly, with

the constant increase in urban population, the total grain consumption in urban areas also increased while that of rural areas decreased. Overall, as per capita annual grain consumption in urban areas has remained a little lower than in rural areas, the total grain consumption on the TP has actually slightly decreased. The total grain consumption on the TP in 2016 was 327.22 × 10^4 t. Due to a concomitant decrease in the supply-demand gap since 1989 (6.21 × 10^4 t/a), the self-sufficiency rate increased at an average of 1.97%/a.

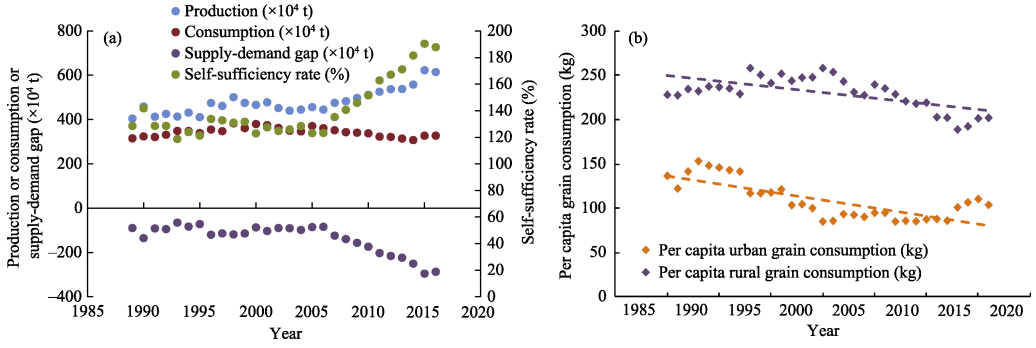

Figure 2 Changes in capacity for grain self-sufficiency on the Tibetan Plateau

3.2 Spatiotemporal differences in grain self-sufficiency at the provincial level

3.2.1 The current situation

Between 2010 and 2016, the parts of Yunnan, Sichuan, Qinghai, Gansu and Tibet had higher than 100% of grain self-sufficiency rates in an order from high to low (Table 2). Considering the two largest provincial-level regions, average annual grain production of Qinghai (124.61 × 10^4 t) was higher than that of Tibet (96.86 × 10^4 t); the grain self-sufficiency rate of Qinghai (162.50%) was also higher than that of Tibet (134.96%) because of similar consumption (Figure 3).

3.2.2 Change of provincial grain self-sufficiency capacity

In terms of grain production, the parts of Yunnan, Gansu, Xinjiang, and Tibet encompassed by the plateau all experienced continuous increase over the study period, while the parts of Sichuan and Qinghai provinces underwent increasing-decreasing-increasing trends, with average annual production values of 135×10^4 t and 125×10^4 t, respectively. In terms of grain consumption, the parts of Sichuan, Gansu, Yunnan, and Qinghai encompassed by the plateau all increased initially and then decreased. Consumption between 2010 and 2016 was lower than that between 1985 and 1999 apart from that in the Yunnan component of the plateau. Consumption in Xinjiang and Tibet increased continuously; these reached 2.92×10^4 t and 71.77×10^4 t recently, respectively. Regarding grain self-sufficiency rates between 2010 and 2016, all regions experienced increases between 1985 and 1999, but values for Xinjiang and Gansu components of the plateau remained still less than 100%. In terms of the grain supply-demand gap, Sichuan, Yunnan, Tibet, and Qinghai components of the plateau were all self-sufficient over the four time periods (except for Qinghai during the period of 2000–2009), while Xinjiang and Gansu parts experienced a gap throughout the first three time periods. The average annual grain supply-demand gap for all the provincial-level regions apart from Xinjiang

remained less than zero between 2010 and 2016 (Table 2).

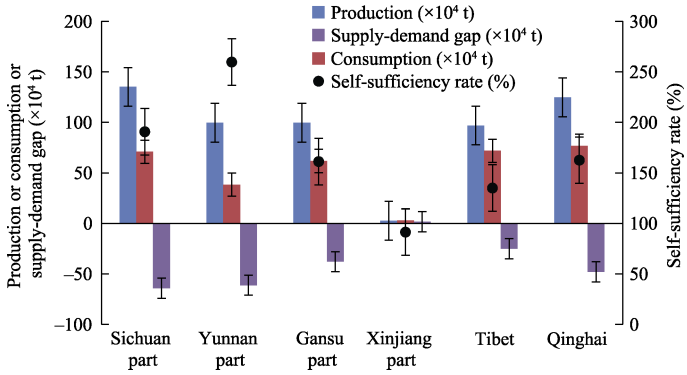

Figure 3 Capacity for grain self-sufficiency in different provincial-level regions that comprise the Tibetan Plateau between 2010 and 2016

Table 2 The changes of capacity for grain self-sufficiency in different provincial-level regions that comprise the Tibetan Plateau between 1985 and 2016

Provincial component	Period	Production (×10⁴ t)	Consumption (×10⁴ t)	Self-sufficiency rate (%)	Supply-demand gap (×10⁴ t)
Sichuan	1985–1989	113.35	79.24	143.05	–34.11
	1990–1999	125.92	82.59	152.47	–43.33
	2000–2009	122.62	79.89	153.49	–42.73
	2010–2016	135.03	70.83	190.63	–64.20
Yunnan	1985–1989	55.50	35.04	158.37	–20.46
	1990–1999	66.98	45.53	147.09	–21.44
	2000–2009	79.70	40.36	197.48	–39.34
	2010–2016	99.59	38.35	259.67	–61.24
Gansu	1985–1989	54.78	64.10	85.47	9.31
	1990–1999	64.35	72.12	89.22	7.77
	2000–2009	76.92	78.98	97.39	2.06
	2010–2016	99.66	61.82	161.20	–37.83
Xinjiang	1985–1989	0.82	1.78	46.16	0.96
	1990–1999	1.19	2.06	57.49	0.88
	2000–2009	1.26	2.25	55.85	1.00
	2010–2016	2.67	2.92	91.32	0.25
Tibet	1985–1989	51.74	39.22	131.94	–12.52
	1990–1999	70.35	49.98	140.77	–20.37
	2000–2009	94.41	64.63	146.07	–29.78
	2010–2016	96.86	71.77	134.96	–25.09
Qinghai	1985–1989	105.08	83.39	126.01	–21.69
	1990–1999	113.32	93.31	121.44	–20.01
	2000–2009	88.84	91.67	96.91	2.83
	2010–2016	124.61	76.68	162.50	–47.92

3.3 Spatiotemporal variation in grain self-sufficiency at the county level

3.3.1 The current situation

Counties characterized by grain production values more than 15.00 × 10^4 t on the TP are

mainly distributed in eastern Qinghai, central-south Tibet, and in areas adjacent to Sichuan-Tibet (Figure 4a). Counties with annual grain consumption values higher than 5.00 × 10^4 t are mainly distributed around urban areas in eastern Qinghai and central-south Tibet, including Xining, Lhasa, Xigaze, Qamdo, and Shangri-La (Figure 4b).

Fifty-nine percent of counties with grain self-sufficiency rates higher than 100% are mostly distributed in the basins of 'the Yarlung Zangbo River and its two tributaries' (including Linzhou, Dazi, Qushui, Lazi and Bailang counties as well as Duilong Deqing District), in areas adjacent to Sichuan-Tibet (including Chayu, Daocheng, Muli, and Batang counties), in regions around Qinghai Lake (including Menyuan, Gonghe, and Guinan counties), and in agricultural areas of eastern Qinghai (including Huangzhong, Ping'an and Ledu counties as well as Minhe Hui and Tu Autonomous County), where cropland area is large (Figures 4c and 4d). Average grain self-sufficiency rates for counties (districts) within Lhasa City (237.68%) were higher than those recorded for other cities. Indeed, apart from urban areas within Xining, self-sufficiency rates for other counties within this city were all greater than 100% (between 133.20% and 392.08%). Counties (districts) within the cities of Xigaze (197.63%), Linzhi (170.32%), and Changdu (100.99%) all conform to this trend. Most recorded grain self-sufficiency rates were higher than 100% with the exception of Gongbujiangda County within Xigaze City. Rates recorded for Jiangda, Wuqi, Chaya, and Basu counties as well as for Karuo District within Changdu City were less than 100% (Figures 1, 4c and 4d).

Counties with grain self-sufficiency rates less than 100% are mainly distributed within animal husbandry areas in the headwater regions of the Yangtze and Yellow rivers (including Zaduo, Zhiduo, Nima, and Gaize counties as well as other animal husbandry regions), in Hoh Xili semi-desert areas (including Ritu and Shuanghu counties), as well as in Qiangtang

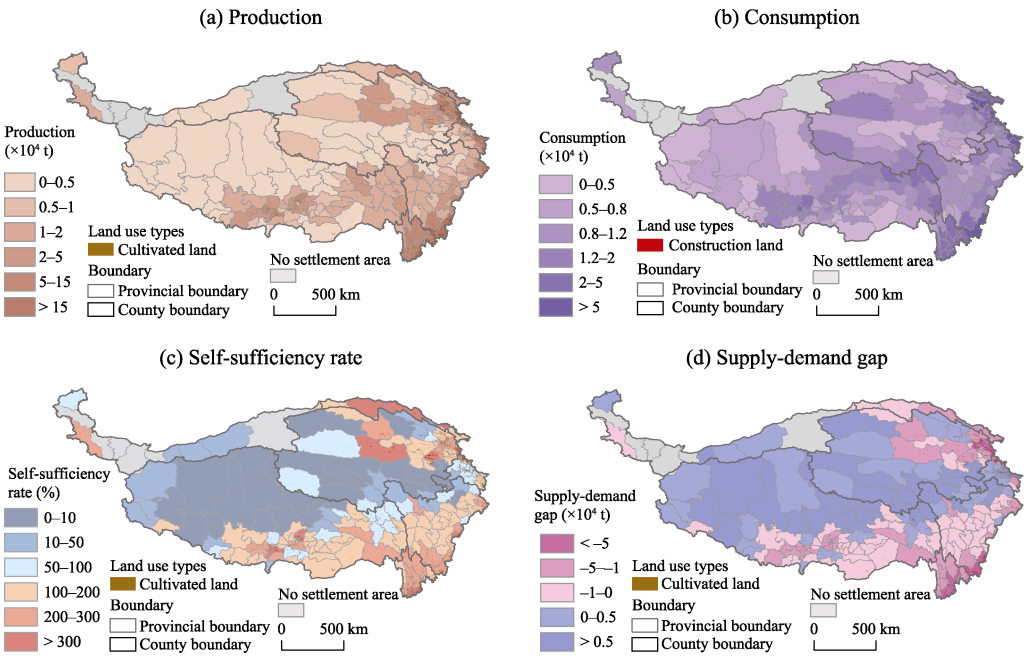

Figure 4 Capacities for grain self-sufficiency at the county level on the Tibetan Plateau between 2010 and 2016

Plateau Tibetan pastoral areas (including Cuoqin, Zhongba, and Geji counties) where annual grain production values are less than 0.50 $\times 10^4$ t.

3.3.2 Changes in capacity for grain self-sufficiency at the county level

Counties that have experienced significant increases in grain production on the TP are mainly distributed within major producing areas in southeastern Tibet. Significant decreases have occurred within Aba Tibetan Autonomous Prefecture in Sichuan Province, in some counties inside Xining City, as well as in Qilian, Gangcha, Yushu, and Maqin counties in Qinghai (Figure 5a). Counties that have experienced a significant increase in grain consumption are mainly distributed within Lhasa, Xigaze, Changdu, and Shannan cities in Tibet; significant reductions have been seen in Xining and Haidong cities as well as in Hainan Tibetan Autonomous Prefecture, in Aba in Sichuan, and in counties within Ganzi Tibetan Autonomous Prefecture in Qinghai (Figure 5b). Counties that have experienced significant increase in grain self-sufficiency values include Linzhou, Bailang, Ganzi, Batang, Muli, Yanyuan, Mangkang, Jiangda, Huangzhong, Minhe, Ledu, Hualong, Xunhua, Menyuan, Guinan, Gonghe, and Ping'an; annual increases of grain self-sufficiency values of these regions are between 0.07% and 12.97%, accounting for 36% of the TP. These regions are mainly distributed in areas adjacent to Sichuan-Tibet, in the southeast of Tibet, and in agricultural areas of eastern Qinghai. Counties that have experienced annual declines in grain self-sufficiency between 0.09% and 8.76% include Duilong Deqing and Naidong districts as well as Qushui, Cuoqin, Bayi, Milin, Lang, Langkazi, Gangcha, Aba, Jiuzhaigou, and Li counties. These regions account for 16% of the TP and are mainly distributed within basins of 'the Yarlung Zangbo River and its two tributaries' in Tibet, as well as around Linzhi City and in Aba Tibetan Autonomous Prefecture in Sichuan (Figure 5c).

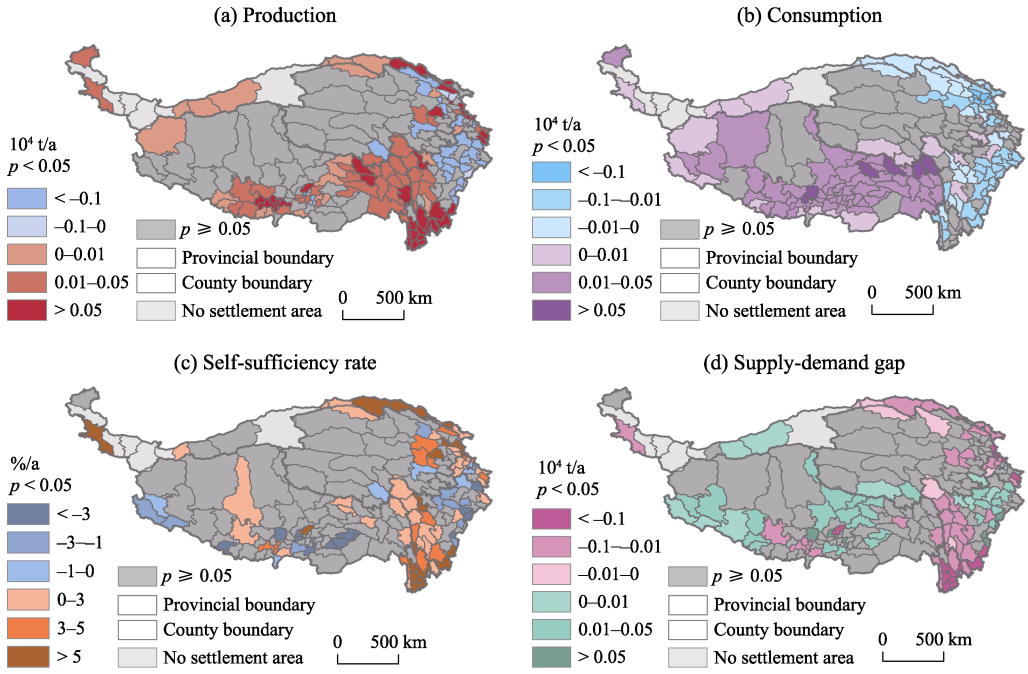

Figure 5 Changes in grain self-sufficiency on the Tibetan Plateau between 1985 and 2016

4 Discussion

4.1 Factors influencing changes in grain self-sufficiency

The factors influencing grain self-sufficiency and changes in this variable on the TP include cropland area, population size, adjustments in the consumption structure of residents, total power of agricultural machinery, regional agricultural production and so on. Cropland area has been the dominant factor influencing spatial patterns in grain self-sufficiency across the TP. Areas characterized by high grain self-sufficiency values are mainly distributed in regions where cropland area is also large, such as the Tibetan River Valley and agricultural areas in eastern Qinghai. Similarly, counties with low grain self-sufficiency tend to have less cropland and are mainly distributed in significant pastoral areas such as in Naqu, Ali, Yushu, and Guoluo counties (Figure 4). Changes in grain production have also been influenced by the sown area of grain and the total power of agricultural machinery. Results reveal that sown area within the main agricultural areas of the TP has decreased over recent decades. Cropland area within the eastern part of Qinghai (including Huangzhong, Ping'an, Minhe Hui, and Tu Autonomous counties as well as Ledu District) decreased from 254.90 km^2 to 125.70 km^2 between 1989 and 2016. Over the same time period, due to a continuous increase in the total power of agricultural machinery from 4.50×10^4 kw to 15.00×10^4 kw, grain production in this region steadily grew.

Change in grain demand on the TP are closely related to population size. Between 1985 and 2016, the per capita annual grain consumption of residents in urban and rural areas decreased by 32.68 kg and 25.94 kg, respectively. Although the overall population of the TP has annually increased by 311.8 thousand persons, the total grain consumption has not changed significantly (Figure 2). The improvement in grain self-sufficiency is related to the distribution of cropland and regional production. Regions that have experienced significant improvement in grain self-sufficiency values are mainly distributed in adjacent areas to Sichuan-Tibet and in agricultural areas of eastern Qinghai where there are more cropland areas and better developed agriculture and animal husbandry (including Chayu, Daocheng, Muli, and Batang counties) (Figures 4 and 5). Values for effective irrigated and grain sown areas as well as for the total power of agricultural machinery were higher in these regions than across the whole of the rest of the TP, leading to marked increases in grain self-sufficiency rates.

4.2 Comparison with previous researches

In previous researches, Gu *et al*. (2000) argued that Tibet would achieve grain self-sufficiency in the 1990s, and Liu *et al*. (2004) also calculated that the grain supply in this region in 2002 was adequate without external grain input. Similarly, Gao *et al*. (2017) concluded that the grain supply in Tibet exceeded demand in 2010. These conclusions are all consistent with our results and show that the provincial grain self-sufficiency rate was higher than 100% in Tibet between 1999 and 2016. In contrast, Shangguan *et al*. (1998) showed that the grain supply in Qinghai was insufficient between 1991 and 1996; this is inconsistent with our results which suggest the grain self-sufficiency rate has not markedly changed and, indeed, was more than 100% between 1991 and 1996. In addition, although total grain con-

sumption on the TP has decreased slightly, we have shown that grain in Qinghai has been sufficient to meet demand. However, Duan *et al*. (2019) concluded that total grain consumption on the TP has increased steadily so that local production cannot meet demand.

Different per capita grain consumption standards were used in previous researches to calculate regional demand. Xie *et al*. (2017) calculated values for per capita grain consumption using per capita food intake from the 'Outline of Food and Nutrition Development in China', and other researchers used the per capita nutritional calorific value of 400 kg extracted from the FAO (Wu *et al*., 2013; Zhou *et al*., 2015; Hu *et al*., 2016). Previous studies also employed different standards of either 400 kg or 300 kg to calculate grain consumption in grain surplus and shortage areas (Feng *et al*., 2009). Similarly, a value of 385 kg has also been used as this is the adult nutritional dietary guidelines requirement for Chinese residents (Jin *et al*., 2016). In one study of grain demand on the TP, per capita grain consumption values in different counties were calculated using security lines of 400 kg, 300 kg, and 200 kg (Duan *et al*., 2019), while other researchers have used consumption from investigations or yearbooks to assess supply and demand in Tibet (Gao *et al*., 2017).

Two key features are highlighted here compared with previous studies. First, the fact that regional heterogeneity was considered when calculating consumption. We used annual per capita grain consumption in urban and rural areas for provincial-level regions on the TP and combined these values with the urban and rural population of each county to obtain values for total grain consumption. This approach enabled us to reflect heterogeneity in different provincial-level regions and also distinguish differences in consumption between urban and rural areas. Per capita grain consumption in urban areas has been lower than in rural areas across the TP; at the same time, the urban population of this region has gradually increased while the rural one has decreased and so total consumption across the plateau has also fallen slightly. Secondly, we have analyzed differences in grain self-sufficiency across multiple scales in this study, including regional, provincial, and county levels.

4.3 Study limitations

This study has some limitations. First, due to a lack of detailed data regarding feed, industrial grain and so on in each county, the grain consumption did not include these types of grain in the evaluation of self-sufficiency in this study. In addition, wheat, highland barley, rice, legume, and potato were all included in grain supply calculations, but detailed grain classifications were not included in consumption calculations. Annual grain consumption per person was only assessed here using urban and rural yearbook values. Furthermore, we also did not take into account the impact of the tourist population on grain consumption in this study. Some other studies suggest that the annual grain consumption of the tourist population on the TP reaches 17.95×10^4 t, so the risk of a food security impact remains relatively small (Duan *et al*., 2019).

5 Conclusions

We considered differences in per capita grain consumption in urban and rural areas of the TP, and systematically explored heterogeneity in grain self-sufficiency at regional, provincial,

and county scales between 1985 and 2016. We paid special attention to spatial distributions and trends in grain self-sufficiency at the county scale. The results of this analysis reinforce the scientific basis for regulation of grain supply and demand spatial distribution on the TP.

Between 2010 and 2016 counties with a grain self-sufficiency rate higher than 100% account for 59% of total regions. Counties where there has been an obvious increase in this rate account for 36%, while 16% experienced a significant decrease. In terms of counties with self-sufficiency rates higher than 100%, 82% and 92% of this group are located in the basins of 'the Yarlung Zangbo River and its two tributaries' as well as agricultural areas in eastern Qinghai because these places have more cropland. We also reveal obvious spatio-temporal differences in grain self-sufficiency across the TP. Production has significantly increased in agricultural and pastoral areas across southeastern and southern Tibet, while consumption has increased markedly in central-south and southeastern regions. It is also clear that the grain self-sufficiency rate has increased significantly in agricultural areas across eastern Qinghai as well as in southeastern Tibet. Headwater regions of the Yangtze and Yellow rivers as well as the Qiangtang Plateau have experienced insufficiencies in grain supply. Overall, grain on the TP is able to meet local demand. However, spatial variations in grain supply and demand on the plateau are significant. It is important that we emphasize strengthening grain supply and regulation in particular in areas near major cities.

References

Cheng S K, Min Q W, 2002. Strategies of agriculture and animal husbandry development in Tibet Autonomous Region. *Resources Science*, 24(5): 1–7. (in Chinese)

Cheng S K, Shen L, 2000. The strategy of regional sustainable development on the Qinghai-Tibet Plateau. *Resources Science*, 22(4): 2–11. (in Chinese)

Duan J, Xu Y, Sun X Y, 2019. Spatial patterns and their changes of grain production, grain consumption and grain security on the Tibetan Plateau. *Journal of Natural Resources*, 34(4): 673–688. (in Chinese)

Fukase E, Martin W, 2016. Who will feed China in the 21st century? Income growth and food demand and supply in China. *Journal of Agricultural Economics*, 67(1): 3–23.

Gao L W, Xu Z R, Cheng S K *et al*., 2017. Food security situation and major grain supply and demand on the Tibetan Plateau. *Journal of Natural Resources*, 32(6): 951–960. (in Chinese)

Gu S Z, 2000. On food security situation and countermeasures in Tibet Autonomous Region. *Journal of Natural Resources*, 15(4): 305–314. (in Chinese)

Hu T, Ju Z S, Zhou W, 2016. Regional pattern of grain supply and demand in China. *Acta Geographica Sinica*, 71(8): 1372–1383. (in Chinese)

Jin T, Xia Q, Yue M M *et al*., 2016. Supply-demand balance evaluation in grain-feed perspective: The case of Jiangsu Province. *Economic Geography*, 36(6): 136–141. (in Chinese)

Liu J, Li X M, Zhong X H, 2004. Consumption structure of food and the countermeasure of grain in Tibet. *Journal of Mountain Science*, 22(3): 286–291. (in Chinese)

Min Q W, Cheng S K, Zhong Z M, 2003. Development orientation of agriculture and animal husbandry in Qinghai-Tibet Plateau. *Research of Agricultural Modernization*, 24(5): 335–338. (in Chinese)

Nie F Y, Bi J Y, Zhang X B, 2010. Study on China's food security status. *Agriculture and Agricultural Science Procedia*, 1, 301–310.

Qi X X, Vitousek P M, Liu L M, 2015. Provincial food security in China: A quantitative risk assessment based on local food supply and demand trends. *Food Security*, 7(3): 621–632.

Shangguan Z P, 1998. Grain production and sustainable development in Northwest China. *Transactions of the Chinese Society of Agricultural Engineering*, 14(2): 19–24. (in Chinese)

Shen R P, Guo Q, Chen P P *et al*., 2019. Impact of high resolution atmospheric forcing and plant functional types datasets on soil temperature simulation in the Tibetan Plateau. *Plateau Meteorology*, 38(6): 1129–1139. (in Chinese)

Su B Q, Wang Y Y, Shangguan Z P, 2017. Effect of reverting farmland to forest project in Northwest China on grain production and farmers' livelihood. *Bulletin of Soil and Water Conservation*, 37(2): 247–252. (in Chinese)

Wang Q, Liu X H, Yue T X *et al*., 2015. Using models and spatial analysis to analyze spatio-temporal variations of food provision and food potential across China's agro-ecosystems. *Ecological Modelling*, 306: 152–159.

Wang W, Yan H M, Yang Y Z *et al*., 2019. Evaluation of land resources carrying capacity of Tibetan counties based on dietary nutritional demand. *Journal of Natural Resources*, 34(5): 921–933. (in Chinese)

Wen J, 2000. Functions, patterns and countermeasures combining farming with stock breeding on the Qinghai-Tibet Plateau. *Journal of Natural Resources*, 15(1): 56–60. (in Chinese)

Wu J S, Jiang P P, Huang X L *et al*., 2013. Spatial-temporal analysis of grain supply and demand in rapid urbanization regions in Eastern China: A case study of Guangdong Province. *Journal of Natural Resources*, 28(2): 253–265. (in Chinese)

Xie G D, Cheng S K, Xiao Y *et al*., 2017. The balance between grain supply and demand and the reconstruction of China's food security strategy in the new period. *Journal of Natural Resources*, 32(6): 895–903. (in Chinese)

Xu Z R, Zhang Y L, Cheng S K *et al*., 2017. Scientific basis and the strategy of sustainable development on the Tibetan Plateau. *Science & Technology Review*, 35(6): 108–114. (in Chinese)

Xu Z Y, Song Z W, Deng A X *et al*., 2013. Regional changes of production layout of main grain crops and their actuation factors during 1981–2008 in China. *Journal of Nanjing Agricultural University*, 36(1): 79–86. (in Chinese)

Yang C Y, Shen W S, Li H D, 2015. Response of grain yield in Tibet to climate and cropland change during 1985–2010. *Transactions of the Chinese Society of Agricultural Engineering*, 31(17): 261–269. (in Chinese)

Zhang Y L, Liu L S, Wang Z F *et al.*, 2019. Spatial and temporal characteristics of land use and cover changes on the Tibetan Plateau. *Chinese Science Bulletin*, 64(27): 2865–2875. (in Chinese)

Zheng H L, Fang S F, Liu C C *et al*., 2019. Dynamics of monthly vegetation activity and its responses to climate change on the Tibetan Plateau. *Journal of Geo-information Science*, 21(2): 201–214. (in Chinese)

Zhou Z Y, Gao M J, Li Q X *et al*., 2015. Estimation of the primary products demand in China based on the balanced diet. *Chinese Journal of Agricultural Resources and Regional Planning*, 36(4): 85–90. (in Chinese)