Research Article
Spatial-temporal Variation Characteristics of Grain Yield per Unit Area and its Balanced Increasing Potential in China

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Abstract: The aim of this study is to provide assistance decision for grain yield in China, which can provide basis for reasonable layout of grain production project. Based on the statistical data of 2301 counties in China, using spatial autocorrelation analysis method, spatial changes of grain yield per unit area at county level in China during 1990-2010 were discussed and then the increase potential of grain yield per hectare and total yield at regional scale were calculated. The results showed that: (1) Grain yield per unit area at county level showed the evident pattern "High in the northern while low in the southern" and "High in the eastern and western while low in the middle"; The average grain yield per hectare increased by 1040.74 kg/hm^2 during 1990-2010 and the increment of grain yield per unit area descended from North to South at county level. (2) Grain yield per unit area at county level in China had a strong spatial autocorrelation. The counties with "High-High" and "Low-Low" correlation were the majority. Counties with significant "High-High" correlation in 2010 were mostly located in plain area, while counties with significant "Low-Low" correlation were mainly distributed in Hengduan Mountainous Area, Inner Mongolia steppe Area, etc. (3) Two thousand three hundred and one counties were divided into 41 first-grade regions and 115 sec-grade regions according to the coupled conditions of cultivation system regionalization and LISA cluster map. The total potential output of China was $1.77×10^8$ tons.

Keywords: China, grain yield per unit area, potential yield, spatial autocorrelation analysis method

INTRODUCTION

Grain yield continues to increase steadily is the basic guarantee for food security, which is important to world stability and social development (Rondaninia *et al*., 2012). On the basis of solid sown area, increasing per unit area yield of grain is the main way to increase grain output in the future (Liu *et al*., 2013). In order to provide scientific basis for grain yield planning and efficient utilization of agricultural resources, systematic analysis of spatial-temporal differentiation of grain yield per unit area, scientific calculation of improvement in potential yield of regional grain should be taken (Bai *et al*., 2013).

In recent years, domestic and foreign scholars have made depth analysis of spatial-temporal pattern, influencing factors and yield-increasing potential of per unit area from different perspectives (He *et al*., 2008; Cheng, 2009). With the diversification of data acquisition methods and more attention paying to "spatial interaction", more researches are focusing on per unit area yield of grain and spatial heterogeneity of input factors by spatial economic model (Cheng *et al*., 2007). According to literature search, the researches on per unit area yield of grain have converted their research scales from national scale or provincial scale to municipal scale or county scale. Research methods mainly adopt variation coefficient, multiple regression analysis, ridge regression analysis, etc., but more and more researches adopt spatial econometric model. Research contents concerning about the status of per unit area yield of grain, while paying attention to reveal spatial temporal evolution rule and spatial agglomeration characteristics of per unit area yield. Researches on yield-increasing potential adopt mechanism method (Zheng *et al*., 2013) and focus on the region itself, but think less about the relationship between regions. The unbalanced development of per unit area yield of one same grain in different regions caused by significant differences in cultivated land resource endowment and social economic development level (Bi *et al*., 2008; Zhang and Qin, 2011; Zhang *et al*., 2006), thus affecting the overall increase in regional grain yield. So it is an effective method to measure regional yield-increasing potential through type partition based on spatial agglomeration model of per unit area yield of grain and cultivation system regions with measurement of regional yield-increasing potential by regional linkages. Therefore, in order to provide assistance support for grain yield in China, this

study adopts per unit area yield data in 1990 and 2010 at county scale with application of spatial autocorrelation analysis to explore the spatial characteristics of per unit area yield of grain and with cultivation system regions to estimate regional yield-increasing potential.

RESEARCH METHODS AND DATA SOURCES

Spatial autocorrelation analysis model: ESDA method discovers spatial agglomeration and spatial anomaly through visualization of spatial distribution pattern of objects, which provides an effective method to investigate spatial distribution pattern of different regional attribute values and relative changes in spatial differences. Spatial autocorrelation analysis can be divided into global spatial autocorrelation analysis and local spatial autocorrelation analysis. Global spatial autocorrelation analysis model can be used for analysis of overall regional spatial association and difference degrees; Global Moran's I index is more commonly used (Lu and Mei, 2007; Wang *et al*., 2009):

$$I_t = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(x_{i_t} - \bar{x}_t)(x_{j_t} - \bar{x}_t)}{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \sum_{i=1}^{n} (x_{i_t} - \bar{x}_t)^2} \quad (1)$$

wherein I_t represents global Moran index of per unit area yield of grain in the year of t, while its value range is $[-1, 1]$, $I<0$ represents negative spatial autocorrelation, $I = 0$ represents spatial uncorrelation, $I>0$ represents positive spatial autocorrelation, while the bigger the absolute value of I, the stronger the spatial autocorrelation. x_{it} and x_{jt} represent per unit area yield of grain in County i and County j in the year of t. w_{ij} represents spatial weighted matrix of research object. Local spatial autocorrelation analysis can measure local spatial association and difference degrees between each area and its surrounding areas, while visualization of difference patterns can be achieved with Moran scatter diagram, etc. Local Moran's I is always used for measurement of spatial difference degrees and significance between Area i and its surrounding areas:

$$I_{it} = \frac{(x_{i_t} - \bar{x}_t) \sum_{j=1}^{n} w_{ij}(x_{j_t} - \bar{x}_t)}{\sum_{j=1, j \neq i}^{n} x_{j_t}^2 /(n-1) - \bar{x}_t^2} \quad (2)$$

The meaning of symbols in the formula is the same as that in Formula (1), drawing LISA aggregation diagram according to Local Moran's I index.

Measurement of regional equilibrium potential yield increase: Regional equilibrium potential yield increase is a kind of potential to achieve regional equilibrium

development and scale benefit based on the foundation of interregional spatial relationships with the basically same premise of light, heat, water, soil, natural resources and topographic and geomorphic conditions, while development goal of grain yield is relatively clear (Bai *et al*., 2013). When agricultural production level has developed to a certain degree, grain yield will certainly transforms to regional development, scale development and centralized development (Deng *et al*., 2013), per unit area yield of grain in one region will be significantly affected by per unit area yield of grain in surrounding areas (Liu *et al*., 2011; Deng *et al*., 2013). Therefore, this study makes comprehensive consideration of LISA diagram for per unit area yield and divides yield-increasing type areas according to cultivation system regions, sets the highest per unit area yield of the county in each type area as its target per unit area yield of the type area and then estimates yield-increasing potential according to yield gap between actual per unit area yield and target per unit area yield of each county:

$$Z_p = \sum_{k=1}^{N_1} \sum_{i=1}^{N_2} (x_{kmax} - x_{ik}) \times M_{ik} \quad (3)$$

where,
Z_p = Equilibrium yield-increasing potential
N_1 = The quantity of equilibrium yield increase type areas
N_2 = The quantity of counties in type area
x_{kMax} = Target per unit area yield of type area k
x_{ik} = Actual per unit area yield of County i in type area k
M_{ik} = Grain acreage of County i in type area k

Data source and data processing: This research reveals spatial-temporal characteristics of per unit area yield with its yield-increasing potential at county scale and secondary regions of cultivation system. After carding, taking the year of 2010 as standard to correct county-level administrative division unit, uniformly merging the area under jurisdiction of prefecture-level cities into urban areas of prefecture-level cities, while 2301 units at county scale in total, not including Hongkong, Macao and Taiwan. Grain yield and grain acreage data at county scale in 1990 comes from Thematic Database for Human-earth System (http://www.data.ac.cn/newzrzy), while relevant data in 2010 comes from statistical yearbooks of provinces, cities and countries. Standard cultivation system refers to farming methods that have been used or will be widely used under current socio-economic level, production condition and technical level; these methods are able to satisfy social needs and good for production or to maximize the productive potential of lands without causing ecological damage. Cultivation system district based on heat, moisture, topography, social and economic conditions as well as other indexes, the whole country is divided into 12 primary regions and 40 secondary regions (Liu, 2002; GB/T 28407-2012,

2012), while Hengduan Mountainous region is regarded as a secondary region because Hengduan Mountainous region in primary region doesn't divide into secondary regions, therefore 41 secondary regions in total, with basically the same natural resources and environment in each secondary region of cultivation system. Grain total output, grain acreage and per unit area yield for each secondary region of cultivation system can be obtained respectively by combining all the data.

RESULT ANALYSIS

Spatial-temporal variation of per unit area yield at county scale: In 2010, total grain output in China was 5.46×10^8 t, increasing by 1.22×10^8 t in 20 years, average annual growth rate was 1.02%; per unit area yield increased from 3932.84 kg/hm^2 in 1990 to 4973.58 kg/hm^2 in 2010, average annual growth rate was 1.18%. Partial correlation analysis was made for relevant data relating to grain from 1990 to 2010 by SPSS 15.5. Correlation coefficients between grain yield, per unit area yield and grain acreage were 0.8648 and -0.3299, respectively, which mean increasing per unit area yield was an effective method to increase grain yield during the period, while decline in grain acreage limited steady increase in grain yield.

As apparent from Table 1 and Fig. 1, 1243 counties' per unit area yield in 1990 were lower than national average value (3932.84 kg/km^2) in 1990. One hundred and nineteen counties' per unit area yields were equal to or greater than 6000 kg/hm^2 and 605 counties' per unit area yields were between 4500 and 6000 kg/hm^2. In 2010, average per unit area yield was 4973.58 kg/hm^2, the highest average yield was 12071 kg/hm^2, the lowest average yield was 230 kg/hm^2, while counties with relatively high per unit area yield were dominant. Counties with relatively high per unit area yield were mainly distributed in two kinds of regions: one kind of regions were located in plain area in mid-east region with flat terrain, relatively thick soil layer, plentiful water resources and suitable light and heat conditions, these regions have built relatively complete agricultural infrastructure with relatively high per unit area yield based on relatively developed socioeconomic level; the other kind of regions were located in plateau area in Northern China and Western China, such as Northern Xinjiang Irrigation Area, Hetao-Yinchuan Plain, while the counties in these areas were in high elevation with longer illumination time, large

temperature difference between day and night, therefore grain crops always had relatively high per unit area yield and good quality with the premise of sufficient water resources for irrigation. Counties with relatively low per unit area yield were centralized distributed in first ladder (Qinghai-Tibet Plateau) and second ladder (excluding Northwest China) with large undulating terrain, thin soil layer, frequent natural disasters, incomplete agricultural infrastructure, as well as low and unstable per unit area yield.

The change characteristics of per unit area yield at county scale between 1990 and 2010 were as follows (Fig. 1):

- Clear growth trend of per unit area yield, per unit area yield of 2046 counties increased, accounting for 88.92% of total counties.
- Per unit area yield of 678 counties were equal to or greater than 6000 kg/hm^2, increasing by 559 counties since 1990; the number of counties with per unit area yield of 4500~6000 kg/hm^2 increased by 295, while counties of per unit area yield of 3000~4500 and 2000~3000 kg/hm^2, less than 2000 kg/hm^2 reduced by 399, 304 and 146, respectively.
- Increment of per unit area yield showed "lower in the south and higher in the north" clearly. Counties with per unit area yield of equal to or greater than 3000 kg/hm^2 were mainly distributed in Northern China, while per unit area yield of most counties in Songnen Plain Area, Huang-Huai Plain Area, Hebei-Shandong-Henan Low-lying Plain Area and Western Xinjiang increased rapidly; increase in per unit area yield of Southern China and Southwestern China were not obvious, increment of per unit area yields in most counties was less than 2000 kg/hm^2. In addition, per unit area yield of counties in West Sichuan Plain, East Sichuan Low Hilly Mountain Area and South China Low Plain Area increased slowly.

Agglomeration characteristics of per unit area yield at county scale: Global Moran's I values of per unit area yield at county level in 1990 and 2010 were 0.6786 and 0.6276, respectively. These values showed positive spatial autocorrelation, which mean per unit area yield at county scale shows spatial concentration distribution. Measure significance of Global Moran's I by *Z* method,

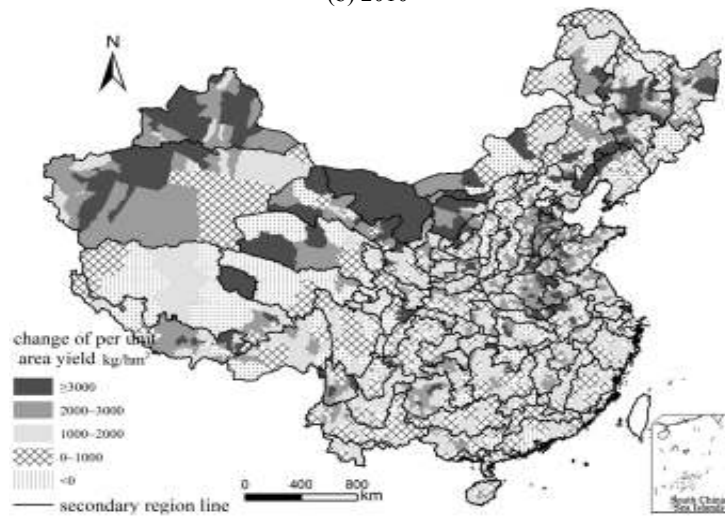Table 1: Distribution of counties with different grain production in China

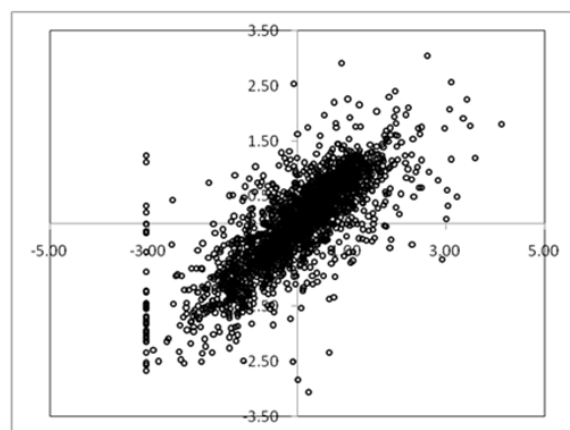| Grain yield per unit area kg/hm^2	1990		2010	
	County number	Ratio of grain yield/%	County number	Ratio of grain yield/%
≥6000	119	11.02	678	49.11
4500~6000	605	40.17	900	36.06
3000~4500	886	34.91	487	11.89
2000~3000	450	11.42	146	2.34
0~2000	202	2.48	56	0.57
No grain production	39		34	
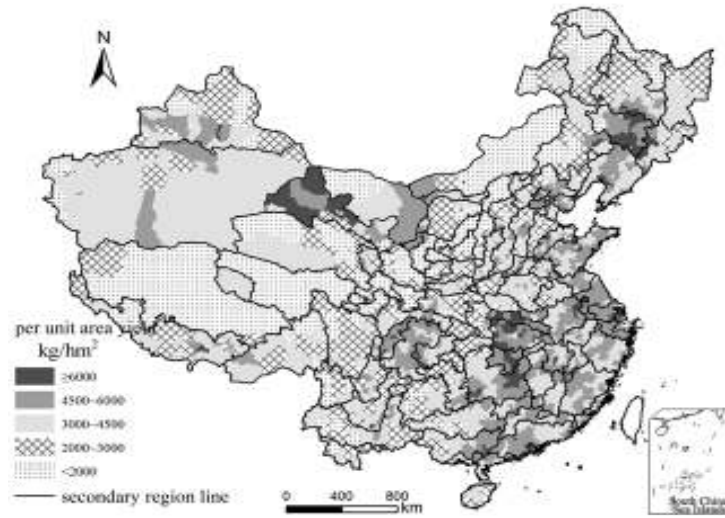
(a) 1990
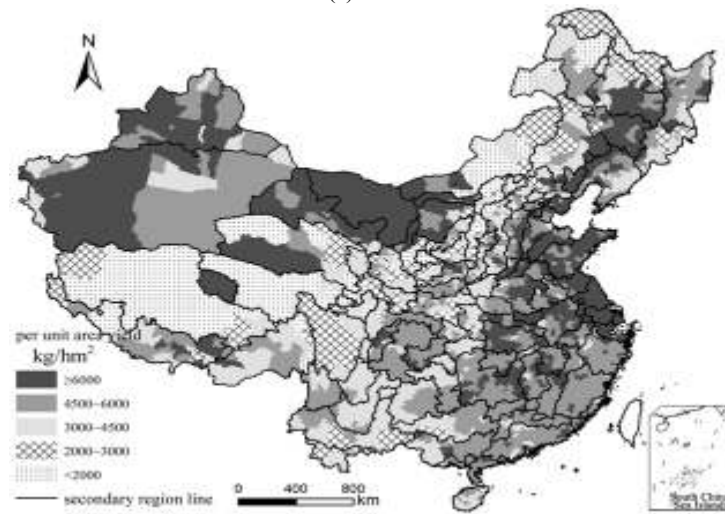
(b) 2010
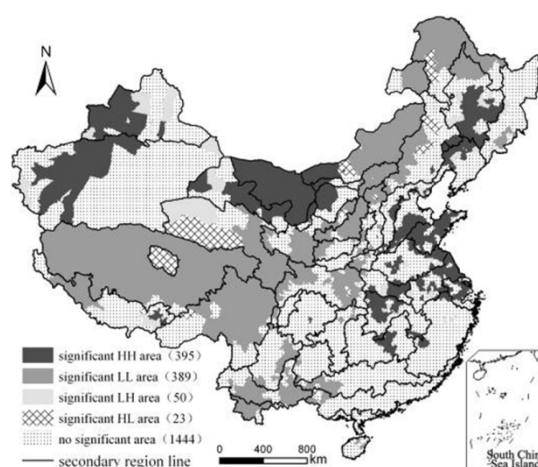

(c) 1990~2010

Fig. 1: Spatial pattern of grain yield per unit area at county level in China

(a) Moran scatter map

significant HH area（395）
significant LL area（389）
significant LH area（50）
significant HL area（23）
no significant area（1444）
secondary region line

0 400 800 km

South China
Sea Islands

(b) LISA cluster map

Fig. 2: Moran scatter map and LISA cluster map for the grain yield per unit area at county level in China in 2010

which mean spatial autocorrelation was significant under confidence value of 99.9%. Local differentiation of per unit area yield manifested as four spatial agglomeration types: HH Type area (LL Type area) represented small spatial differences in per unit area yield at county scale, while both per unit area yields of the county and its surrounding counties were relatively high (low); HL Type area (LH Type area) represented large spatial differences in per unit area yield, per unit area yield of the county was relatively high (relatively low), but per unit area yields of its surrounding counties were relatively low (relatively high), which formed local heterogeneous "hot spot" ("cold spot").

As apparent from Fig. 2a, 1734 counties were distributed in the first quadrant and the third quadrant, which showed significant spatial correlation of per unit area yield in local scope and spatial aggregation structure of high-value (low-value) area of per unit area yield; a part of counties were distributed in HL quadrant and LH quadrant, which showed spatial heterogeneity of per unit area yield of some counties. Combing Moran scatter diagram with LISA

significance level to obtain Local Moran's I diagram with significance level of 5%, which in turn contributed to further analysis of spatial autocorrelation degree of per unit area yield. As seen in Fig. 2b, significant HH areas were distributed in Songnen Plain Area, Huang-Huai Plain Area, Hebei-Shandong-Henan Low-lying Plain Area, etc. Significant LL areas were mainly distributed in Hengduan Mountainous Area, Shanxi-Shaanxi Hilly Valley Area, Inner Mongolia Steppe Area, etc.; there were small amount of significant LH (HL) areas with scattered distribution; other counties were not representative.

Distribution characteristics of grain yield between secondary regions of cultivation system:

- In 2010, Songnen Plain Area and Huang-Huai Plain Area were highest-yield areas to produce total grain output and per unit area yield, total grain outputs of Songnen Plain Area and Huang-Huai Plain Area were accounted for 11.91% and 11.66% of total output in China, respectively; while total
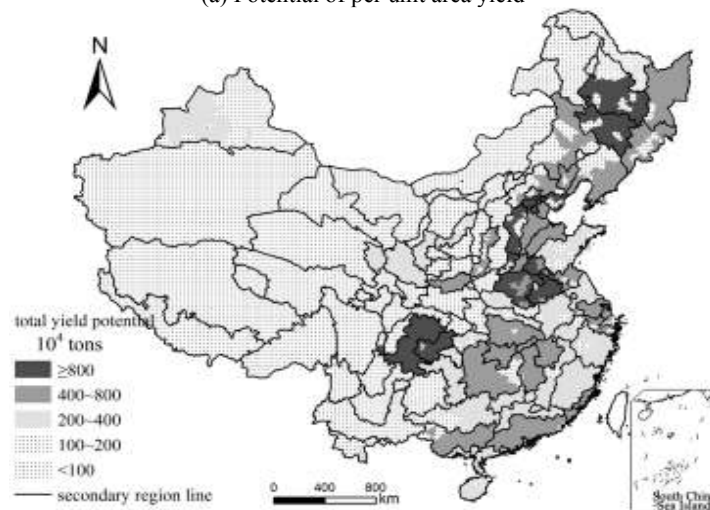
grain outputs of Yanjiang Plain Area, Hebei-Shandong-Henan Low-lying Plain Area, Jianghuai Plain Area, East Sichuan Low Hilly Mountain Area, Shandong Hilly Area, West China Hilly and Mountainous Area, Yanshan-Taihang Mountain Piedmont Plain Area were accounted for 4% to 8% of total output; total grain outputs of Inner Mongolia Steppe Area, Hexi Corridor Area, Shanxi-Shaanxi Hilly Valley Area, Hengduan Mountainous Area, Houshan Bashang Plateau Area, South Tibet Plateau Valley, Southern Qinghai and Northern Tibet Plateau area, Alxa Plateau and other areas were accounted for 1% of total output in China; increase speeds of 18 areas were faster than national average level during 1990-2010, Songnen Plain Area, Huang-Huai Plain Area, Hebei-Shandong-Henan Low-lying Plain

Area, Changbai Mountain Area in Sanjiang Plain, Northern Xinjiang Irrigation Area, Daxing'anling Mountain Area and Xiaoxing'anling Mountain Area and other areas had relatively large growth rates; while increase speeds of 23 areas were slower than national average level, which cause dramatic decline in proportions of total grain outpus of Yanjiang Plain Area, South China Low Plain Area, Eastern China Hilly and Mountainous Area, East Sichuan Low Hilly-mountain Area, West China Hilly and Mountainous Area, West Sichuan Plain and Nanling Hilly Area.

- From perspective of per unit area yield, counties of relatively high per unit area yield were mainly distributed in Eastern and Northern China, per unit area yields of Songnen Plain Area, Changbai Mountain Area in Sanjiang Plain, Liaoning Plain
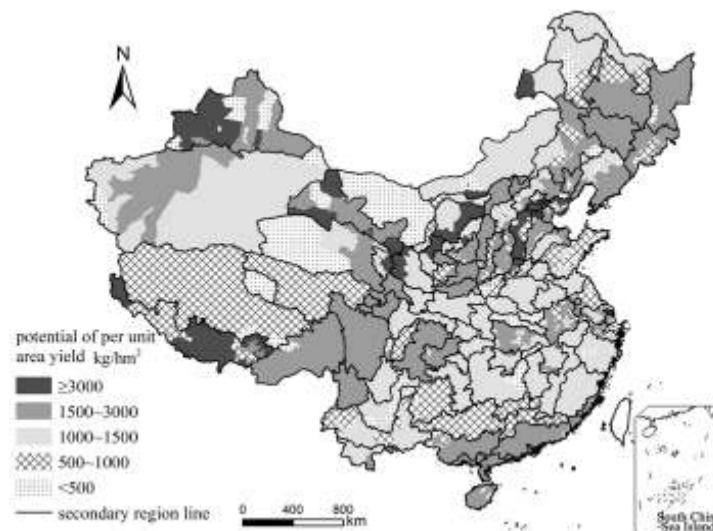
(a) Potential of per unit area yield

(b) Total yield potential

Fig. 3: Regionalization of balanced potential to increase grain production in China

Area, Hebei-Shandong-Henan Low-lying Plain Area, Yanshan Taihang Mountain Piedmont Plain Area, Huang-Huai Plain Area, Yanjiang Plain Area, Hexi Corridor Area, Hetao-Yinchuan Plain Area, Northern Xinjiang Irrigation Area and other areas increased significantly; while counties in Central and Southwestern China had relatively low per unit area yield.

Equilibrium yield-increasing potential of grain in China: Achieve superposition of secondary regions of cultivation system with LISA aggregation diagram by ArcGIS, based on these results, dividing China into 115 equilibrium yield-increasing type areas according to local spatial autocorrelation analysis results of per unit area yield and the principles of operability, simple and practical. Calculating yield-increasing potential of each county based on grain acreage of each county in 2010 and further summarying of total yield-increasing potential of various type areas and China (Fig. 3):

- There were large differences in target per unit area yields between secondary regions of cultivation system, target per unit area yields of Northern Xinjiang Irrigation Area, Hexi Corridor Area, South Tibet Plateau Valley, Alxa Plateau were all beyond 8000 kg/hm^2; target per unit area yields of Songnen Plain Area, Yanshan-Taihang Mountain Piedmont Plain Area, Liaoning Plain Area, Southern and Eastern Xinjiang Basin Oasis Area, Hebei-Shandong-Henan Low-lying Plain Area, Hetao-Yinchuan Plain were relatively high, between 7000 and 8000 kg/hm^2; target per unit area yields of Southern Qinghai and Northern Tibet Plateau area, Houshan-Bashang Plateau Area, Shanxi-Shaanxi Hilly Valley Area, Daxing' anling Mountain Area and Xiaoxing' anling Mountain Area and other areas were less than 4000 kg/hm^2.
- There were large differences in per unit area yield potential and total yield potential between different kinds of areas. There were great potentials for per unit area yields of Southern Ningxia-Longzhong-Qingdong Loess Hilly Area, Yanshan-Taihang Mountain Piedmont Plain Area, Inner Mongolia Steppe Area, Hexi Corridor Area, South Tibet Plateau Valley, Northern Xinjiang Irrigation Area and other areas, but little potentials for per unit area yields of Alxa Plateau, West Sichuan Plain, West Henan Mountain and Hilly Area; total yield potential was 1.77×10^8 t, Songnen Plain Area, Huang-Huai Plain Area, Yanjiang Plain Area and East Sichuan Low Hilly-Mountain Area had great total yield potentials and total yield potential for each area was more than ten million tons. Total yield potential was considerably larger than grain yield increase task as specified by Grain Production Capacity Planning of Newly Increasing 100 billion Catties (2009 to 2020). As long as we

develop appropriate land management measures and efficient incentive policies for grain yield will ensure the goals of grain yields to be achieved.

DISCUSSION AND CONCLUSION

Per unit area yield of grain increased from 3932.84 kg/hm^2 in 1990 to 4973.58 kg/hm^2 in 2010, per unit area yield of 2046 counties increased, increment of per unit area yield showed the law of "lower in the south and higher in the north" clearly. Spatial agglomeration characteristics of per unit area yield of grain at county scale were significant. Whole country was divided into 41 primary regions and 115 secondary regions based on LISA distribution diagram of cultivation system regions and per unit area yield of grain at county scale, total yield potential in China was 1.77×10^8 t. These results prove to conform with actual situations in China fairly, measurement results based on per unit area yield potentials at county scale and total yield potential will contribute to the distribution of yield-increasing projects and provide the basis for reasonably distribute high-standard basic farmland construction projects and low yield land improvement projects. This study reveals spatial-temporal differentiation characteristics and local homogeneity of change of grain yield per unit area from perspective of inter regional relationship by exploratory spatial data analysis method, which provides a fresh idea to divide yield-increasing type areas scientifically. While, per unit area yield of grain will be affected by a variety of factors, even increasing methods and specific measures to achieve grain yield increase in different kinds of type areas are quite different. Therefore, systematic research on driving mechanism for per unit area yield increase, clarify limiting factors for per unit area yield increase in different kinds of type areas and develop appropriate yield-increasing measures for different kinds of type areas are the issues that need deep exploration.

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