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Potential promoted productivity and spatial patterns of medium- and low-yield cropland land in China

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Abstract: With a continuously increasing population and better food consumption levels, improving the efficiency of arable land use and increasing its productivity have become fundamental strategies to meet the growing food security needs in China. A spatial distribution map of medium- and low-yield cropland is necessary to implement plans for cropland improvement. In this study, we developed a new method to identify high-, medium-, and low-yield cropland from Moderate Resolution Imaging Spectroradiometer (MODIS) data at a spatial resolution of 500 m. The method could be used to reflect the regional heterogeneity of cropland productivity because the classification standard was based on the regionalization of cropping systems in China. The results showed that the proportion of high-, medium-, and low-yield cropland in China was 21%, 39%, and 40%, respectively. About 75% of the low-yield cropland was located in hilly and mountainous areas, and about 53% of the high-yield cropland was located in plain areas. The five provinces with the largest area of high-yield cropland were all located in the Huang-Huai-Hai region, and the area amounted to 42% of the national high-yield cropland area. Meanwhile, the proportion of high-yield cropland was lower than 15% in Heilongjiang, Sichuan, and Inner Mongolia, which had the largest area allocated to cropland in China. If all the medium-yield cropland could be improved to the productive level of high-yield cropland and the low-yield cropland could be improved to the level of medium-yield cropland, the total productivity of the land would increase 19% and 24%, respectively.

Keywords: food security; light use efficiency model; cropland productivity; high-, medium- and low-yield cropland; potential productivity

1 Introduction

Continuous population growth and food consumption have placed huge pressure on agriculture and natural resources, and greatly increased food production is needed to ensure global food security (Foley *et al*., 2011). Grain production in most arable land is far below the po-

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tential productivity of high-producing cropland under similar climatic conditions (Foley *et al*., 2011; Tilman *et al*., 2011). There is therefore great potential to improve the actual productivity and the land use efficiency of arable land. A substantial rise in food production can be achieved through the adoption of new technologies, improved water and nutrient-use efficiency, and advanced agricultural management (Foley *et al*., 2011; Foley *et al*., 2005; Shi *et al*., 2010; Tilman *et al*., 2011; Zhang *et al*., 2005). China is the world's largest producer and consumer of agricultural products, and is faced with increasing resource constraints to agricultural development (Shi *et al*., 2010). The sustained and steady growth of agriculture in China will have to rely on an acceleration of agricultural science and technological innovation that will improve the efficiency of resource utilization[1)] and result in efficient, high-yielding agriculture coordinated with sustainable resource use.

To improve the basic conditions for agricultural production, the Chinese government initiated a medium- and low-yield cropland improvement project in 1988, and a high-standard cropland construction project in 2009. From 1988 to 2012, approximately 661 million hectares (ha) of cropland[2)] in 2045 counties and 222 state-owned farms were covered by these types of projects. In 2013, the State Council of the People's Republic of China approved the "National Comprehensive Agricultural Development and High-standard Farmland Construction Plan" with a goal of 800 million mu (15 mu = 1 ha) of high-standard cropland and improved medium- and low-yield cropland by 2020. Therefore, an accurate and explicit spatial expression of medium- and low-yield cropland distribution is necessary before implementing a cropland promotion plan.

Current studies show that high-, medium-, and low-yield cropland can be identified using the following three methods. The first one is the cropland quality method based on field survey data. This method classifies cropland into quality levels using obstacle factors as key indicators. High-yield cropland has few limitations, and classification of medium- and low-yield cropland is conducted according to different limitation levels (Lin, 2008). The second one is the average yield method based on statistical data (Lin, 2008; Wu, 2009). A certain deviation (e.g., 15% or 50 kg) from the average yield is taken as the upper or lower limit of medium-yield cropland. The third one is the potential productivity method (Lin, 2008), in which classification of high-, medium-, and low-yield cropland is conducted according to the ratio values of their actual productivity to potential productivity. These methods have both advantages and disadvantages. The cropland quality method requires systematic and detailed fieldwork to evaluate the limiting factors of cropland; it is labor intensive, requires capital investment, and is time consuming, and it is difficult for near real-time monitoring and evaluation of cropland quality on a large scale. The average yield method is hard to avoid the interference of cropping system adjustments and crop variety changes. In addition, county-based statistical data is important for qualifying the actual productivity of cropland at a national or regional scale; however, it cannot evaluate the quality of specific plots. The potential productivity method needs an estimation of the maximum potential productivity of cropland and involves complex computational processes. Therefore, a novel method for spatially explicit monitoring and effective evaluation of cropland quality on a

1) Chen Xiwen: stick to the path of agricultural modernization with Chinese characteristics, http://cpc.people.com.cn/GB/64162/82819/114926/114927/6840448.html (2008/01/30)

2) Wang Guangkun: http://www.farmer.com.cn/xwpd/btxw/201312/t20131206_920451.htm (2013/12/06)

large scale is needed to improve the sustainable use of arable land.

The development of satellite observation techniques provides data access for land use change and the monitoring of crop growth for different spatial-temporal scales (Li Folin, 2005). The development of productivity models makes them increasingly applicable to the simulation of the productivity of various ecosystems and their responses to climate and land use changes at multiple scales (Huang *et al*., 2008; Li Folin, 2005; Wang *et al*., 2010; Yan *et al*., 2012). Large developments in remote sensing technology and remote sensing models for cropland productivity make it feasible to propose a novel classification method of high-, medium-, and low-yield cropland. Ecosystem net primary productivity (NPP) represents the accumulated organic matter of plants per unit area and time. It directly represents cropland actual productivity and provides a unified measurement for the productivity of various crops. Remote sensing based NPP estimation has become an effective and feasible metric to monitor high-, medium-, and low-yield cropland. The VPM (Vegetation Photosynthesis Model) is one of the important methods for estimating NPP based on MODIS data. The VPM can estimate ecosystem productivity in regions with multiple cropping systems (Yan *et al*., 2012; Yan *et al*., 2009). In this study, we simulated cropland NPP using a VPM model and MODIS data with a spatial resolution of 500 m. We then identified high-, medium-, and low-yield cropland according to the derived standard in each cropping system zone of China. We finally estimated the level of potential productivity of medium- and low-yield cropland.

2 Data and methods

2.1 The VPM model

The VPM (Xiao *et al*., 2004) is a satellite-based light use efficiency model used in estimating ecosystem productivity. The model has been validated by CO_2 flux observation data in different cropland ecosystems, including spring corn (Wang *et al*., 2010) in northeast China and a winter wheat-summer maize rotation in Yucheng (Yan *et al*., 2009).

In the VPM, gross primary productivity (GPP) is estimated based on Monteith's equation; estimation of GPP is expressed as:

$$GPP=\varepsilon_g \times FPAR_{chl} \times PAR \quad (1)$$

where ε_g is the light use efficiency (μmol CO_2/μmol PPFD), $FPAR_{chl}$ is the fraction of photosynthetically active radiation (PAR) absorbed by leaf chlorophyll in the canopy, and PAR is the photosynthetically active radiation (μmol photosynthetic photon flux density, PPFD).

Light use efficiency (ε_g) is affected by temperature, water, and leaf phenology:

$$\varepsilon_g = \varepsilon_0 \times T_{scalar} \times W_{scalar} \times P_{scalar} \quad (2)$$

where ε_0 is the maximum radiation use efficiency (μmol CO_2/μmol PAR). The value of ε_0 was calculated from NEE (Net Ecosystem Exchange) and incident PAR observed from CO_2 eddy flux tower sites (Yan *et al*., 2012). T_{scalar}, W_{scalar}, and P_{scalar} are the scalars for the effects of temperature, water, and leaf phenology on the light use efficiency of vegetation, respectively. More detailed methods for calculating the parameters above have been reported by Kalfas *et al*. (2011).

NPP is estimated as the ratio of autotrophic respiration to GPP. According to the experimental results of respiration rate on wheat, sunflower, sorghum, and beans, the ratio value of autotrophic respiration to GPP generally remains constant and equal to 0.42 (Albrizio *et al*., 2003; Ball, 1996; Cheng *et al*., 2000; Gifford, 1995).

2.2 Data

(1) Cropland distribution

Cropland distribution data came from the National Land-Use/Land-Cover Dataset (NLCD) with a mapping scale of 1:100 000. The dataset was interpreted from Landsat TM/ETM images with a 30-m spatial resolution and its accuracy was validated by extensive field survey data.

(2) Cropland productivity

National cropland NPP during 2000–2008 was simulated using a VPM model. In order to eliminate effects from climate fluctuation and agricultural management changes, the average NPP of 2001–2010 was taken as the cropland productivity for high-, medium-, and low-yield cropland classification.

(3) Cropping system zones of China

To take into account the regional differences in natural and climatic conditions, a map of China's cropping system zones was used in this study. China's arable land is divided into three cropping zones, 12 major zones, and 38 sub-zones in terms of heat, water, topography, cropping systems, crop types, and socio-economic conditions (Figure 1). Within each cropping sub-zone, a standard for high-, medium-, and low-yield cropland classification was developed in this study.

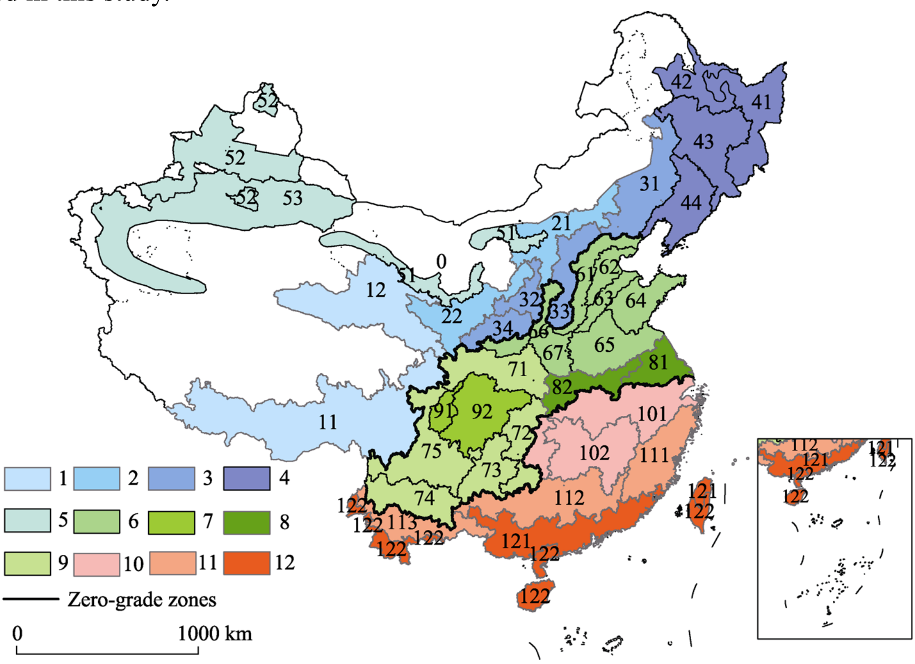

Figure 1 Map of China's cropping system zones. The zero-grade zones classify the land as single-, double-, and triple-cropping zones. The numbers, ranging from 1 to 12, represent the codes of major zones and are marked in the same color. Thirty-eight sub-zones are labeled by numbers.

The driving data for the VPM model included the Enhanced Vegetation Index (EVI) and Land Surface Water Index (LSWI), temperature and PAR, in which EVI and LSWI were calculated from MODIS surface reflectance product (MOD09A1, http://www.edc.usgs.gov/)

with 500 m spatial and 8-day temporal resolution. Temperature data was derived from meteorological observations provided by the China Meteorological Data Sharing Service System (http://www.cma.gov.cn/2011qxfw/2011qsjgx/). PAR data was retrieved from MODIS surface reflectance product.

2.3 High-, medium-, and low-yield cropland classification method

In this study, medium-, and low-yield cropland indicated the cropland with a lower or much lower productivity output than their potential under the current natural and socio-economic conditions. High-yield cropland referred to highly productive cropland with few limiting factors to its agricultural production.

To avoid misclassification caused by mixed pixels, we chose pixels with a cropland area percentage of not less than 50% within each 500 m x 500 m grid for the classification criteria, and obtained frequency distribution histograms of NPP in different agricultural regions. There were four typical frequency distribution histograms in 38 sub-zones (Figure 2), and each of them had a concentrated distribution. The NPP values at two inflection points before and after the concentrated distribution were regarded as the boundary values, and the grids outside the intervals with low frequency were taken as noise. NPP_a and NPP_b represented two inflection points (NPP_a<NPP_b); NPP_{dif} was defined as the difference between NPP_b and NPP_a. Theoretically, the proportion of high-, medium-, and low-yield cropland area should be the same, which means NPP_a+1/3*NPP_{dif} should be the upper limit of low-yield cropland,

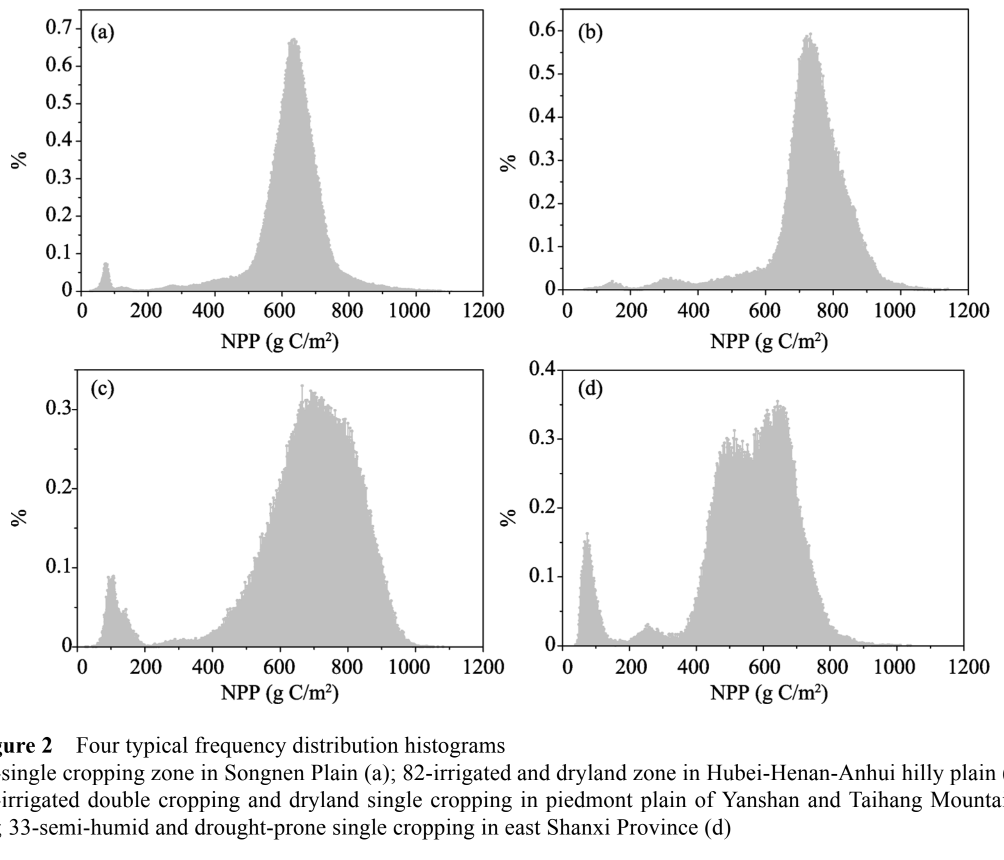

Figure 2 Four typical frequency distribution histograms
43-single cropping zone in Songnen Plain (a); 82-irrigated and dryland zone in Hubei-Henan-Anhui hilly plain (b); 61-irrigated double cropping and dryland single cropping in piedmont plain of Yanshan and Taihang Mountains (c); 33-semi-humid and drought-prone single cropping in east Shanxi Province (d)

and NPP_b–1/3*NPP_{dif} should be the lower limit of high-yield cropland. However, considering the continuous cropland improvement projects in recent years, the proportions for the three types of cropland were adjusted to 30%, 35%, and 35%, respectively. The boundaries for high-, medium-, and low-yield cropland are expressed as follows:

Upper limit for low-yield cropland = $NPP_a + NPP_{dif}$*30%

Lower limit for high-yield cropland = $NPP_b - NPP_{dif}$*35%

3 Results

3.1 Spatial patterns of high-, medium-, and low-yield cropland

The proportional areas of high-, medium-, and low-yield cropland in China were approximately 20.66%, 39.56% and 39.78%, respectively. High-yield cropland is mainly distributed in the North China Plain, the middle and lower reaches of the Yangtze River Plain, Sichuan Basin, central Jilin, and northeastern Liaoning. These regions provide the best conditions for crop growth with flat terrain and abundant water resources. A small amount of high-yield cropland is distributed in central Shaanxi, northern Ningxia, central and southern Gansu, and northwestern Xinjiang. Although these regions have a relatively poor climate conditions, natural rivers ensure water supply and agricultural development, so they offer a greater productive potential than other cropland in the same agricultural region. Medium-yield cropland is mainly concentrated in the Northeast China Plain, Sichuan Basin, southern and central Henan, and northern Anhui, most of which are surrounding or close to high-yield cropland. Low-yield cropland is distributed in regions with poor natural geographic and climatic conditions, such as the Loess Plateau, the Yunnan-Guizhou Plateau, and the farming-pastoral ecotone of Inner Mongolia (Figure 3).

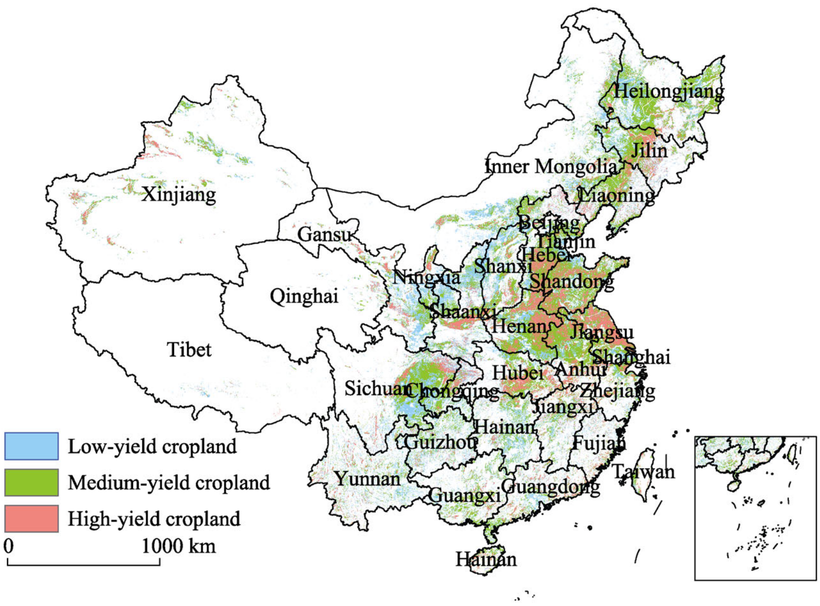

Figure 3 The distribution map of high-, medium-, and low-yield cropland in China

Besides temperature and water conditions, topography is an important factor causing regional differences in cropland productivity. In this study, degrees of relief were extracted from a 1-km digital elevation model (DEM) with an appropriate analysis window of 5 km × 5 km (Zhang *et al.*, 2012). The regions with a relief degree lower than 30 m were defined as plain areas and regions with a relief degree higher than 30 m were defined as hilly and mountainous areas (Liu *et al.*, 2001). In China, 40% of cropland is located in plain areas, while 60% of cropland is located in hilly and mountainous areas. In the plain areas, medium-yield cropland accounted for 48.14%, while high- and low-yield cropland accounted for 27.95% and 23.91%, respectively. In the hilly and mountainous areas, low-yield cropland accounted for the largest area, being 49.15%, and proportions of medium- and high-yield cropland were 34.61% and 16.24%, respectively (Figure 4). In general, about 75% of low-yield cropland was located in the hills and mountains, and the area of medium-yield cropland distributed on the plains was similar to that of the hills and mountains, while proportions of high-yield cropland distributed on the plains and in the hilly and mountainous areas were 53% and 47%, respectively.

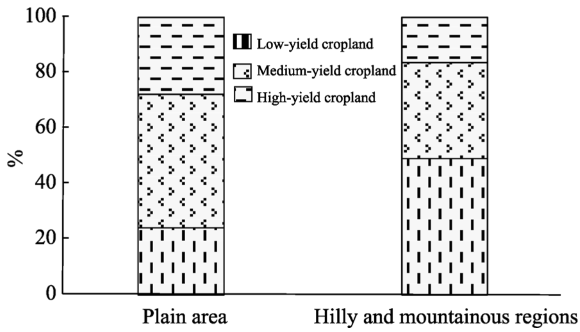

Figure 4 The composition of different terrain areas and croplands

The five provinces with the largest high-yield cropland areas were Henan, Shandong, Jiangsu, Hebei, and Anhui located in the Huang-Huai-Hai Plain region, followed by Hubei, Jilin, and Sichuan provinces. The spatial distribution of high-yield cropland in the above eight provinces was concentrated, and the sum of these high-yield areas accounted for 57.3% of the national high-yield cropland area. Medium- and low-yield cropland was mainly located in Heilongjiang, Sichuan, Inner Mongolia, Henan, and Hebei, accounting for 34.88% of the national medium-, and low-yield cropland area. There were 12 provinces (autonomous regions) in which the proportion of high-yield cropland was greater than the national average (20.66%); Jiangsu ranked first with approximately 50% of high-yield cropland. There were 17 provinces (autonomous regions and municipalities) with proportional areas of low-yield cropland greater than the national average (39.78%; Figure 5).

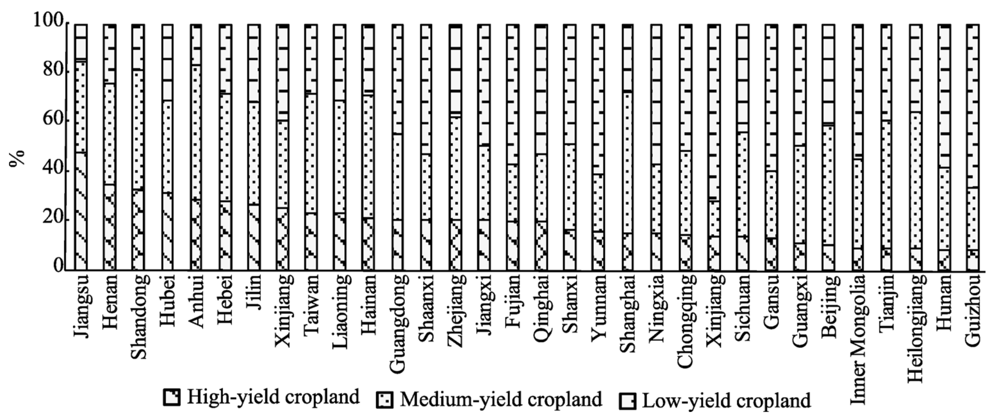

Figure 5 The proportions of high-, medium-, and low- yield cropland in each province

3.2 Potential promoted productivity of medium- and low-yield cropland

Medium- and low-yield cropland refers to arable land that has a potential for increased productivity, because their current productivity levels are far below their potential productivity under the current natural and social conditions. The summed area of medium- and low-yield cropland accounted for 79.34% of the total cropland area in China. In this study, it was assumed that promoted medium- and low-yield cropland had the potential to reach new levels of productivity that may be as high as high-yield cropland in the same sub-zone of the cropping system zones. Therefore, the promoted potential of medium- and low-yield cropland productivity after reformation could be estimated according to the difference between the lower limit for high-yield cropland productivity and the upper limit for medium- or low-yield cropland productivity in each sub-zone. We suggest that low-yield cropland can reach medium-yield levels and that medium-yield cropland can reach high-yield levels, through the reformation of these arable lands. The average productivity of high-, medium-, and low-yield cropland in sub-zones is defined as P_{high}, P_{medium}, and P_{low}, respectively, while P_{medium}-P_{low} and P_{medium}-P_{low} represent the promoted potential for medium- and low- yield cropland productivity (Table 1 and Figure 6).

Table 1 Promoted potential of medium- and low-yield cropland productivity in sub-zones (gC/m^2/a)

Sub-zone code	Promoted potential of low-yield cropland productivity	Promoted potential of medium-yield cropland productivity	Sub-zone code	Promoted potential of low-yield cropland productivity	Promoted potential of medium-yield cropland productivity
11	167.53	214.61	65	135.99	91.91
12	149.05	134.14	66	154.66	157.73
21	80.97	115.43	67	91.62	87.16
22	134.49	197.51	71	145.93	138.42
31	120.70	129.34	72	128.45	101.59
32	67.47	95.10	73	82.74	80.06
33	122.54	122.51	74	269.63	241.69
34	122.43	145.19	75	150.37	163.29
41	89.15	97.85	81	190.49	135.47
42	75.86	122.82	82	93.59	110.83
43	84.80	80.20	91	79.49	72.63
44	100.80	66.66	92	86.92	124.33
51	238.04	195.18	101	174.25	178.35
52	214.61	248.09	102	131.90	117.79
53	225.30	190.01	111	197.00	248.66
61	159.29	150.06	112	146.24	119.47
62	126.33	120.05	113	247.75	266.32
63	138.81	112.36	121	206.51	216.96
64	147.89	117.72	122	297.01	321.38

The productivity of medium- and low-yield cropland in China was 49,263.07×10^4 tC/a and 15,859.72×10^4 tC/a. The promoted potential of medium- and low-yield cropland productivity was approximately 9318.65×10^4 tC/a and 3813.85×10^4 tC/a, respectively. Thus, the productivity of medium- and low-yield cropland productivity would increase 18.92% and

24.05%, respectively. The top five provinces with the highest promoted potential of low-yield cropland productivity were Yunnan, Sichuan, Heilongjiang, Inner Mongolia, and Guangdong; their promoted potential was higher than 200×10^4 tC/a. The high promoted potential in Yunnan, Sichuan, and Inner Mongolia benefited from the large areas of low-yield cropland, while the high promoted potential of productivity per unit area in low-yield cropland was the main reason for the high potential promoted productivity in Guangdong (Table 2 and Figure 6).

Table 2 Production capability and potential promoted productivity of low-yield cropland in each province

Province	Area proportion of low-yield cropland (%)	Low-yield cropland productivity (×10^4 C)	Proportion of low-yield cropland productivity (%)	Potential promoted productivity (×10^4 C)	Increase rate %	Proportion of potential promoted productivity (%)
Heilongjiang	7.96	1732.78	10.93	258.18	14.90	6.77
Jilin	3.29	452.45	2.85	88.00	19.45	2.31
Liaoning	2.78	270.01	1.70	50.67	18.77	1.33
Beijing	0.28	51.19	0.32	15.38	30.04	0.40
Tianjin	0.38	90.19	0.57	21.86	24.24	0.57
Hebei	3.85	662.04	4.17	173.34	26.18	4.55
Shandong	2.70	440.02	2.77	108.70	24.70	2.85
Henan	3.60	1021.36	6.44	175.70	17.20	4.61
Shanxi	4.18	569.75	3.59	141.79	24.89	3.72
Shaanxi	5.39	430.27	2.71	97.09	22.56	2.55
Gansu	5.54	520.49	3.28	163.77	31.46	4.29
Xinjiang	3.26	413.12	2.60	157.81	38.20	4.14
Inner Mongolia	8.75	1008.00	6.36	235.99	23.41	6.19
Ningxia	1.48	161.57	1.02	68.00	42.09	1.78
Qinghai	0.61	22.78	0.14	9.06	39.80	0.24
Tibet	0.46	19.03	0.12	10.77	56.60	0.28
Jiangsu	1.42	337.51	2.13	102.14	30.26	2.68
Anhui	1.85	476.93	3.01	104.79	21.97	2.75
Hubei	2.89	376.33	2.37	86.22	22.91	2.26
Hunan	4.98	699.15	4.41	174.32	24.93	4.57
Jiangxi	3.09	532.08	3.35	114.66	21.55	3.01
Zhejiang	1.48	480.30	3.03	154.58	32.18	4.05
Shanghai	0.17	44.21	0.28	14.97	33.86	0.39
Guangdong	2.75	679.24	4.28	231.58	34.09	6.07
Guangxi	3.56	532.55	3.36	169.57	31.84	4.45
Fujian	1.75	521.27	3.29	162.21	31.12	4.25
Hainan	0.35	95.89	0.60	40.13	41.85	1.05
Taiwan	0.26	78.64	0.50	31.66	40.26	0.83
Sichuan	7.54	1772.73	11.18	265.77	14.99	6.97
Yunnan	5.91	751.06	4.74	292.76	38.98	7.68
Chongqing	2.79	468.50	2.95	64.14	13.69	1.68
Guizhou	4.69	148.30	0.94	28.23	19.04	0.74

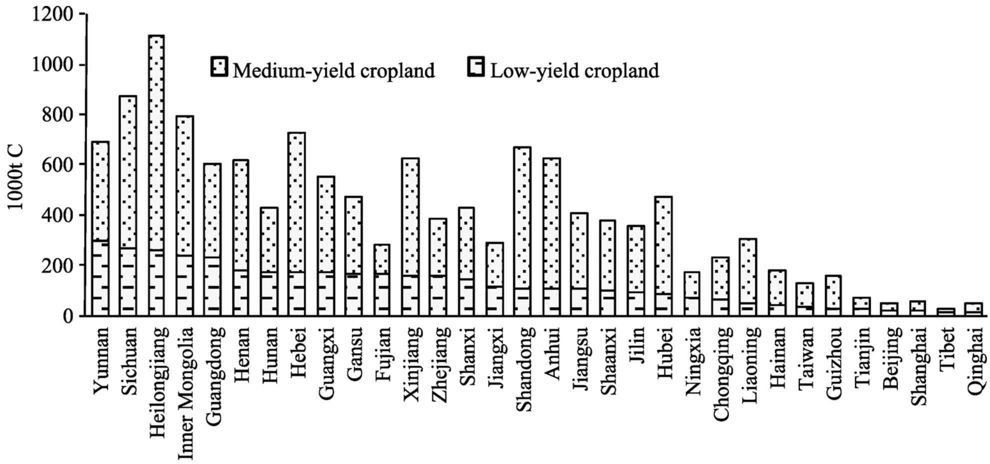

Figure 6 Potential promoted productivity in each province (ordered by total amount)

The top five provinces for promoted potential in medium-yield cropland were Heilongjiang, Sichuan, Shandong, Inner Mongolia, and Hebei, with a promoted potential above 550×10^4 tC/a; Heilongjiang had the highest potential of approximately 851.49×10^4 tC/a. The high potential in these five provinces was due to the large area of widely distributed medium-yield cropland, although the growth rates were all less than 25%. The area and productivity of medium-yield cropland in Henan and Anhui were higher than those in Hebei and Inner Mongolia, but the promoted potential and growth rate were relatively low. The growth rate of promoted potential for medium-yield cropland was only 13.06% in Henan (Table 3).

The lowest five provinces with promoted potential of medium-yield cropland productivity were those regions with developed economies and small areas of cropland (Beijing, Tianjin, and Shanghai) or regions with poor natural conditions (Qinghai and Tibet). The promoted potential of low- and medium-yield cropland productivity in these regions was less than 25×10^4 tC/a and 50×10^4 tC/a, respectively.

4 Conclusions

A spatial distribution map of medium- and low-yield cropland is necessary for planning cropland improvement and meeting the demand for food security in China. In this study, a spatial distribution map of high-, medium-, and low-yield cropland was developed from satellite observation data at a spatial resolution of 500 m. Based on this map and the estimated actual cropland productivity, the potential productivity from promoting medium- and low-yield cropland was estimated. The results of this study showed that:

(1) The proportional areas of high-, medium-, and low-yield cropland in China were approximately 20.66%, 39.56%, and 39.78%, respectively. About 75% of low-yield cropland was located in the hilly and mountainous areas. In the plain areas, about 48% of the cropland was medium-yield, followed by high-yield cropland (28%), and the low-yield area was similar to the high-yield area.

(2) Of China's medium- and low-yield cropland areas, more than 85% was distributed in Guizhou, Hunan, Heilongjiang, Tianjin, Inner Mongolia, Beijing, Guangxi, Gansu, Sichuan, Xinjiang, and Chongqing. Tibet, Guizhou, and Yunnan had the highest proportional areas

(>60%) of low-yield cropland. The three provinces of Heilongjiang, Sichuan, and Inner Mongolia had the largest cropland area, but their high-yield areas covered no more than 15% of the total cropland area.

Table 3 Production capacity and potential promoted productivity of medium-yield cropland in province

Province	Area proportion of medium-yield cropland (%)	Medium-yield cropland productivity ($\times10^4$ C)	Proportion of medium-yield cropland productivity (%)	Potential promoted productivity ($\times10^4$ C)	Increase rate (%)	Proportion of potential promoted productivity (%)
Heilongjiang	12.53	5591.56	11.35	851.49	15.23	9.14
Jilin	4.50	2027.35	4.12	263.31	12.99	2.83
Liaoning	4.20	1902.89	3.86	251.32	13.21	2.70
Beijing	0.33	154.59	0.31	34.50	22.31	0.37
Tianjin	0.50	228.52	0.46	43.74	19.14	0.47
Hebei	6.07	2731.25	5.54	552.14	20.22	5.93
Shandong	7.06	3542.15	7.19	558.29	15.76	5.99
Henan	6.38	3368.73	6.84	440.08	13.06	4.72
Shanxi	3.08	1272.41	2.58	282.19	22.18	3.03
Shaanxi	2.70	1226.67	2.49	279.82	22.81	3.00
Gansu	2.53	1046.96	2.13	303.88	29.03	3.26
Xinjiang	2.99	1618.20	3.28	465.51	28.77	5.00
Inner Mongolia	5.80	2385.04	4.84	556.47	23.33	5.97
Ningxia	0.73	284.72	0.58	99.90	35.08	1.07
Qinghai	0.32	113.63	0.23	36.18	31.84	0.39
Tibet	0.09	30.99	0.06	13.94	44.97	0.15
Jiangsu	3.58	1908.20	3.87	303.91	15.93	3.26
Anhui	6.18	3316.31	6.73	519.71	15.67	5.58
Hubei	3.60	1871.25	3.80	379.66	20.29	4.07
Hunan	2.85	1543.79	3.13	250.27	16.21	2.69
Jiangxi	1.90	1029.40	2.09	171.48	16.66	1.84
Zhejiang	1.66	849.77	1.72	230.50	27.12	2.47
Shanghai	0.35	168.73	0.34	42.25	25.04	0.45
Guangdong	2.14	1287.21	2.61	367.70	28.57	3.95
Guangxi	2.91	1694.63	3.44	382.28	22.56	4.10
Fujian	0.71	408.86	0.83	118.86	29.07	1.28
Hainan	0.62	445.10	0.90	139.98	31.45	1.50
Taiwan	0.44	292.91	0.59	92.02	31.42	0.99
Sichuan	7.30	3655.76	7.42	603.26	16.50	6.47
Yunnan	2.29	1430.87	2.90	390.90	27.32	4.19
Chongqing	1.88	969.52	1.97	162.34	16.74	1.74
Guizhou	1.78	865.09	1.76	130.82	15.12	1.40

(3) In the case where all medium-yield cropland is improved to high-yield cropland and all low-yield cropland is improved to medium-yield cropland, the productivity of medium-

and low-yield cropland would increase 19% and 24%, respectively. The promoted potential of medium-yield cropland productivity was 2.44 times of that of low-yield cropland.

5 Discussion

Cropland is classified into seven grades according to cropland quality in the "Distribution of medium- and low-yield cropland and the potential of grain productivity in China (1988)." The seven grades are aggregated into high-, medium-, and low-yield cropland. The areas of high-, medium-, and low-yield cropland account for 32.16%, 32.90%, and 34.94% of the national cropland area, respectively (Lin, 2008). According to the "Cropland resources and their development and utilization in China (1992)," based on the average yield method (Agricultural Natural Resources and Agricultural Regional Planning Institute of Chinese Academy of Agricultural Sciences, 1992; Lin, 2008), the proportional areas of high-, medium-, and low-yield cropland are 21.54%, 37.24%, and 41.22%, respectively. Based on the potential productivity method, the area of high-, medium-, and low-yield cropland accounted for approximately 34.92%, 41.95%, and 23.14%, respectively. The proportional area of high-, medium-, and low-yield cropland obtained in this study were similar to those of "Cropland resources and their development and utilization in China." However, the proportional area of high-yield cropland was lower than that of the other two methods. The results of each method have the ability to reflect the regional patterns of cropland quality. However, the difference between the previous studies and our study is that, county scale is the smallest spatial unit that can be identified in the previous studies, while a grid detail of 500 m resolution can be identified in this study.

Faced with limited arable land resources, improving the efficiency of cropland utilization is the only choice for the sustainable development of agriculture and national food security. The detailed spatial patterns of high-, medium-, and low-yield cropland are the basis for a comprehensive improvement of cropland. The notable development of remote sensing technology and ecosystem productivity models made it possible to identify high-, medium-, and low-yield cropland. Remote sensing-based ecosystem productivity models can estimate the spatial patterns of cropland NPP at the grid level and therefore largely improve the spatial precision of high-, medium-, and low-yield cropland distribution relative to traditional county statistics data-based methods. Moreover, remote sensing information can reflect the comprehensive effects of natural conditions and management on crop growth. Based on the cropping system zones of China, high-, medium-, and low-yield cropland are classified under different natural and socio-economic conditions, so cropland quality can be identified region-by-region, rather than classified by a nationwide standard. In this study, cropland productivity was calculated based on 500-m MODIS datasets. To eliminate the effect of mixed pixels on the classification criteria of high-, medium-, and low-yield cropland, the NPP values of pixels with a cropland area proportion of not less than 50% were used in each agricultural region, and cropland was the major land use type. However, this method is not effective to reduce the uncertainty in those pixels with low proportional areas of cropland. Therefore, productivity data at higher spatial resolutions is required for a more accurate planning of medium- and low-yield cropland improvement.

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