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Analysis of photothermic resource use efficiency and potential increases in crop yields in high-yielding regions of eastern Asia

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Abstract

In agronomic management, photothermic resources will play an increasingly important role in boosting crop yields to meet growing demands. This study explored photothermic resource use efficiency and predicted the highest theoretical yield of four crop types (maize, rice, ratoon rice and wheat) in the high-yielding regions of the Northeast plain, Huai Hai Lyrics valley and Yangtze River valley of China spanning a latitudinal range from N25.48° to N45.32°. The radiation production potential (RPP) and thermal production potential (TPP) of the four crop types were analyzed, using indexes of radiation production potential equivalence (RPPE) and thermal production potential equivalence (TPPE). The results showed that RPPE and TPPE varied with crop type, harvest zone and high-yielding areas. For the different crop types, the RPPE and TPPE of ratoon rice (0.7406, 0.7848) were the highest, while the RPPE of winter wheat (0.3041) and TPPE of rice (0.4955) were the lowest. The theoretical yield of maize (15,408.2 kg hm^{-2}) was the highest while that of winter wheat (10,273.4 kg hm^{-2}) was the lowest, and the theoretical yield of ratoon rice (12,245.2 kg hm^{-2}) was higher than that of rice (11,117.7 kg hm^{-2}). By harvest zone, the RPPE of the double harvest zone (0.5105) and TPPE of the single harvest zone (0.7015) were the highest, while the RPPE and TPPE of the triple harvest zone (0.4688, 0.5607) were the lowest. By area, the RPPE of Youxi (0.7406) and TPPE of Huadian (0.9089) were the highest, while the RPPE of Lianyungang (0.3607) and TPPE of Changsha (0.4702) were the lowest. Environmental parameters also impacted crop yield, where fewer hours of solar radiation caused a decline in RPP, while higher air temperatures increased TPP. Radiation was the limiting factor for summer maize, late rice and ratoon rice, while temperature was the limiting factor for winter wheat, spring maize and early rice; radiation was the limiting factor for the triple harvest zone, while temperature was the limiting factor for single and double harvest zones; finally, radiation was the limiting factor for Youxi, Changsha, Jiangsu, Wuxue and Haicheng, while temperature was the limiting factor for Harbin, Huadian, Laizhou, Xinxiang, Wuqiao and Lianyungang. Agricultural techniques also affected yield, where the optimum cultivation models were found to be high density double-planting for summer maize, cultivation in earth furrows for winter wheat, simultaneous optimization of the use of radiation and heat by ratoon rice and boosting of sink capacity and source capacity for rice. In conclusion, latitudinal differences in photothermic resources are poorly utilized, even in high-yielding regions, meaning that all regions including those that already meet their annual targets have the potential to further improve yields. Therefore, crops should be sown early to improve heat use efficiency in areas of low latitude while suitable sowing and harvesting dates should be chosen for high latitudes to improve radiation use efficiency. At the same time, the highest-yielding cultivation mode should be matched to the latitude, such as spring maize planting in Huadian, winter-wheat planting in Laizhou and ratoon rice planting in Youxi.

Keywords: China; agriculture; crop; yield; photothermic resource use efficiency; radiation production potential; radiation production potential equivalence; thermal production potential; thermal production potential equivalence.

Abbreviations: AEZ - agro-ecological zone; EAY - experimental area yield; FY - farm yield; LAI - leaf area index; PAR - photosynthetically active radiation; PUEI - photothermic use efficiency index; RPP – radiation production potential; RPPE - radiation production potential equivalence; RY - record yield; SK_1 - ratio of RY to TPP; SK_2 - ratio of EAY to TPP; SK_3 - ratio of FY to TPP; SK_3-SK_2 - potential increase in yield in the short term; SK_3-SK_1 - potential increase in yield in the medium term; TPP - thermal production potential; TPPE - thermal production potential equivalence.

Introduction

Boosting crop yields is a globally important area of research, given the increasing population, decrease in agricultural acreage, and greater frequency of water shortages (Duvick and Cassman, 1999; Evans and Fisher, 1999; Potop et al., 2010). In 2000, the international journal *Science* interviewed experts who suggested a number of technical means to improve crop yields. Examples included switching to new plant types (Yang et al., 2007), improving plant photosynthesis (Austin, 1999), enhancing the harvest index, and prolonging the growing period (Evans, 1993). Through the efforts of scholars across the world, high-yielding crop techniques are continuing to emerge (Alma et al., 2005; Broadley et al., 2010). However, standards used to measure crop yields and other parameters have been subject to variation (Watson, 1958). Therefore, objective evaluation of techniques and yield levels can be difficult to carry out and incorporate into routine management practices (Paudel and Thapa, 2004; Makoi and Ndakidemi, 2011). In China, significant progress has been made in the quest for high-yielding crops (Zhao et al., 2006). The recorded increase in crop yields has led to the realization that high yields depend greatly on ecological conditions (Lobell and Asner, 2003). Obtaining the highest yield from each season's crops requires making full use of ecological resources and improving micro-ecological environmental conditions, along with management techniques such as switching crop varieties and optimizing cultivation practices (Calvin and Samuel, 2001). Agricultural production has been found to vary with different combinations of ecological factors, such as radiation, light and water (Wolf and van Diepen, 1995; Walker and Schulze, 2008), where the ideal combination of such factors should guarantee high yields (Ileleji et al., 2007). As a result, much research has focused on the relationship between ecological factors and crop productivity, such as the optimum temperature and CO_2 levels for crop growth (Cellier et al., 1993; Krishnan et al., 2007), the link between hours of solar radiation and crop yield (Bradford et al., 2006), and the relationship between rainfall and crop yield (Condon et al., 2002; Orlove et al., 2000). Within this framework, the effect of ecological factors on the physiological mechanisms influencing crop yield has been extensively studied. High yields arise as a result of interactions between ecological factors (Kiniry et al., 2004). However, systematic research on the relationship between ecological factors and high yield crops remains limited.Despite a handful of studies, more research is needed to determine the quantitative relationship between crop yield and ecological factors (Hollinger, 1988). The potential productivity of crops provides a means of quantifying the relationship between crop yield and ecological factors. Cao et al. (1995) developed an ecosystem approach to assess the food production potential and human carrying capacity of China's agro-ecosystem. Thomas (2000) analyzed the time series (1954-1993) of Penman-Monteith evapotranspiration estimates for 65 monitoring stations in mainland China and Tibet. Tao et al. (2005) calculated the potential for crop production on a regional scale using remote sensing. Deng et al. (2006) used satellite images to examine changes in the area of cultivated land and potential agricultural productivity in China. However, while a number of environmental models have been established, ecological conditions in China are highly varied and spread across vast latitudinal ranges (N25.48° to N45.32°). Hence, simulated results will be subject to variation depending on the model used and/or regional differences in parameters. As a result, comparisons of crop production capacity at a national scale have proved difficult, restricting the development of reasonable proposals to further improve crop yields throughout China. Given the above-mentioned problems coupled with the need to estimate the nation's crop production potential, a uniform simulation model is required that uses parameters and indexes common to all regions. Recent research on crop production clarified the relationship between climate and crop yield, in order to formulate yield indexes according to local cropping systems across China (Zhao et al., 2006; Zhang et al., 2007). Hence, the current study analyzed photothermic resource use efficiency to better understand how to increase potential crop yields in the short and medium term. This study also identified the most suitable cultivation techniques to maximize theoretical crop yields, thereby enhancing national food security.

Results

Analysis of the production potential equivalence in high-yielding regions

Local photothermic resource use efficiency was evaluated by introducing the two concepts of radiation production potential equivalence (RPPE) and thermal production potential equivalence (TPPE). The former is the percentage of biomass accounting for RPP, while the latter is the percentage of biomass accounting for TPP. Also used was the photothermic use efficiency index (PUEI), which is the percentage of TPP accounting for RPP. The PUEI was used to identify limiting ecological factors at the local scale (see Table 1).

Analysis of yield for four types of crop in high-yielding regions

Table 1 shows yields with respect to four different crop types and 11 high-yielding regions. The highest crop yield was produced by maize (13,728 kg hm^{-2}), followed by ratoon rice (11,453 kg hm^{-2}), rice (10,673 kg hm^{-2}) and wheat (9,937 kg hm^{-2}). The average yield of summer maize was higher than that of spring maize, while the spring maize yield in the single harvest zone was higher than that in the triple harvest zone. The highest yields of spring maize were recorded in the Huadian region (17,468.3 kg hm^{-2}), while the highest yields of summer maize were recorded in the Laizhou region (19,753.1 kg hm^{-2}). The first season for ratoon rice produced a higher yield than the second season. Late rice produced slightly higher yields than early rice. The highest yield of late rice was recorded in the Lianyungang region (12,975 kg hm^{-2}), while the highest yield of early rice was recorded in the Jiangshan region (11,017.5 kg hm^{-2}). The yield of winter wheat grown in the double harvest zone was slightly higher than that grown in the triple harvest zone. The highest wheat yield was recorded in the Laizhou region (10,539 kg hm^{-2}).

Analysis of RPPE for four types of crop in high-yielding regions

RPPE for the four crop types was highest for ratoon rice (0.7406), followed by maize (0.5995), rice (0.4149) and wheat (0.3041). RPPE from the ratoon season for ratoon rice was higher than that of the first season. Summer maize values were higher than spring maize values. The spring maize value in the

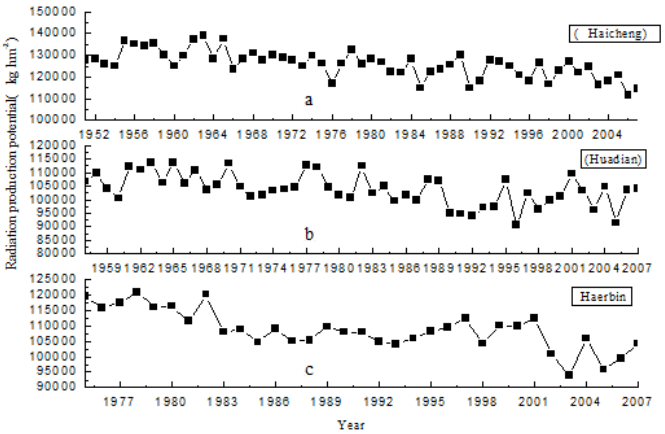

Fig 1. Trends in RPP in Northeast China. (a) Change in RPP from 1952 to 2004 in Haicheng. (b) Change in RPP from 1959 to 2007 in Huadian. (c) Change in RPP from 1977 to 2007 in Harbin.

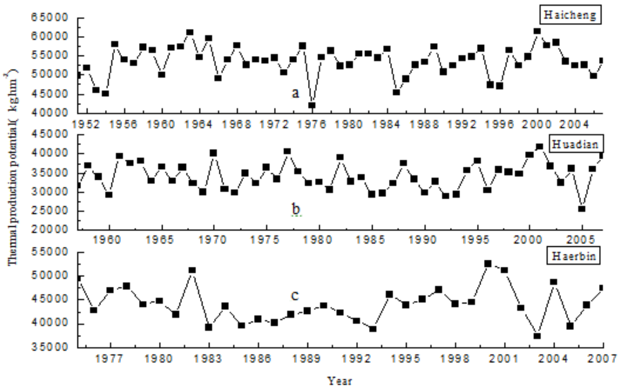

Fig 2. Trends in TPP in Northeast China. (a) Change in TPP from 1952 to 2004 in Haicheng. (b) Change in TPP from 1959 to 2007 in Huadian. (c) Change in TPP from 1977 to 2007 in Harbin.

single harvest zone was higher than that in the triple harvest zone. The highest RPPE value of spring maize was recorded in the Huadian region (0.6076), while the highest RPPE value of summer maize was recorded in the Xinxiang region (0.8240). Early rice had a higher value than late rice, where the highest RPPE value of late rice was recorded in the Wuxue region (0.435) while the highest RPPE value of early rice was recorded in the Jiangshan region (0.4568). Winter wheat in the triple harvest zone had a higher value than that in the double harvest zone, with the highest RPPE value recorded in the Lianyungang region (0.311).

Analysis of TPPE for four types of crop in high-yielding regions

TPPE of the four crop types was highest for ratoon rice (0.7848), followed by maize (0.7074), wheat (0.6076) and rice (0.4932). TPPE of the ratoon season for ratoon rice was far higher than that in the first season. Summer maize had a higher value than spring maize, while spring maize in the single harvest zone had a higher value than that in the triple harvest zone. The highest TPPE value of summer maize was recorded in the Xinxiang region (0.8737), and for spring maize was recorded in the Huadian region (0.9089). Winter wheat in the triple harvest zone had a higher value than in the double harvest zone, while the highest TPPE value was in the Lianyungang region (0.6671). Early rice had a higher value than late rice, with the highest TPPE value of early rice in the Jiangshan region (0.559) and late rice in the Lianyungang region (0.4698).

Analysis of PUEI for four types of crop in high-yielding regions

PUEI ratios of the four crop types were highest for ratoon rice (0.9317), followed by rice (0.8561), maize (0.8448) and wheat (0.5060). The ratio for ratoon rice was higher in the ratoon season than in the first season. Late rice had higher ratios than early rice, with the highest ratio in the Changsha region (0.967) and early rice in the Jiangshan region (0.8172). Spring maize had lower ratios than summer maize, with the ratio of spring maize in the single harvest zone being lower than in the triple harvest zone. The highest ratio of spring maize was recorded in the Haicheng region (0.8241) and summer maize in the Xinxiang region (0.9431). Winter wheat in the double harvest zone had higher ratios than that in the triple harvest zone, with the highest yield recorded in the Xinxiang region (0.6204).

Prediction of theoretical yields in high-yielding regions

The theoretical yields shown in Table 2 were calculated using average meteorological data spanning a 20-year period (1988 to 2007) in high-yielding regions. Theoretical yields were calculated from the values of RPP and TPP, which denote the attained levels of RPP or TPP during the total growing period under current conditions. The theoretical yield in each region was considered to be the highest yield that could be realized using current cultivation techniques. The theoretical yield was highest for maize (14,067 kg hm^{-2}), followed by ratoon rice (12,245 kg hm^{-2}), rice (11,014 kg hm^{-2}) and wheat (10,171 kg hm^{-2}). The datasets indicated that spring maize (12,426 kg hm^{-2}) had a lower theoretical yield than summer maize (15,708 kg hm^{-2}), with the single harvest zone theoretical yield (15,109 kg hm^{-2}) being higher than in the triple harvest zone (9,743 kg hm^{-2}). The first season theoretical yield of ratoon rice (14,974 kg hm^{-2}) was higher than the ratoon season (9,517 kg hm^{-2}). Early rice (10,703 kg hm^{-2}) had a lower yield than late rice (11,325 kg hm^{-2}). Winter wheat in the double harvest zone had a higher yield than in the triple harvest zone.

Increasing production in high-yielding regions over different time periods

Yields were divided into four categories which comprised (1) thermal production potential (TPP), (2) record yield (RY), (3) experimental area yield (EAY), and (4) farm yield (FY). These categories were used to analyze the production potential of the four crop types (maize, wheat, rice and ratoon rice) in the 11 main agricultural regions of China. For the purposes of this analysis, it was assumed that the TPP was 100%. Table 3 shows that the ratio of RY to TPP (SK_1) of the four crop types was greatest for ratoon rice, followed by maize, wheat and rice. The sequences of the ratio of EAY to TPP (SK_2) and the ratio

Table 1. RPP, TPP, RPPE and TPPE of high-yielding areas in China.

	Site	Crop type	RPP (kg hm^{-2})	TPP(kg hm^{-2})	Yield (kg hm^{-2})	RPPE	TPPE	PUEI
Single harvest zone	Harbin	Spring maize	57953.7	42056.6	13905.0	0.4799	0.6613	0.7257
	Huadian	Spring maize	57502.8	38439.7	17468.3	0.6076	0.9089	0.6685
	Haicheng	Spring maize	60256.9	49658.5	13264.5	0.4403	0.5342	0.8241
Double harvest zone	Laizhou	Winter wheat	80610.4	38815.4	10539.0	0.2724	0.5657	0.4815
		Summer maize	52630.9	46173.1	19753.1	0.7506	0.8556	0.8773
	Xinxiang	Winter wheat	65306.3	40517.3	9498.0	0.3030	0.4884	0.6204
		Summer maize	35375.2	33361.0	14574.0	0.8240	0.8737	0.9431
	Wuqiao	Winter wheat	72026.7	38578.9	9793.5	0.3162	0.5904	0.5356
		Summer maize	36023.8	33545.6	11604.8	0.5966	0.6406	0.9312
Triple harvest zone	Lianyungang	Winter wheat	66525.3	31012.1	9930.0	0.3110	0.6671	0.4662
		Late rice	60795.2	54149.8	12975.0	0.4104	0.4698	0.8907
	Wuxue	Early rice	46282.8	33433.9	10192.5	0.4078	0.5645	0.7224
		Late rice	43349.1	41695.4	9993.0	0.4350	0.4522	0.9619
	Jiangshan	Early rice	47291.3	38645.3	11017.5	0.4568	0.5590	0.8172
		Late rice	57232.9	54348.0	10656.0	0.3651	0.3845	0.9496
	Changsha	Spring maize	41812.3	33667.4	9411.0	0.4413	0.5481	0.8052
		Late rice	49265.4	47640.3	9342.0	0.3793	0.3922	0.9670
	Youxi	First season rice	53648.2	47344.7	14334.0	0.5239	0.5936	0.8825
		Ratoon season rice	14926.2	14640.6	8572.5	0.9572	0.9759	0.9809

Table 2. Theoretical yield for the total growing season in each high-yielding area of China

	Site	Crop type	RPP(kg hm^{-2})	TPP(kg hm^{-2})	Theoretical yield(kg hm^{-2})
Single harvest areas	Harbin	Spring maize	58287.0	39125.1	15063.2
	Huadian	Spring maize	53836.0	33242.8	15106.6
	Haicheng	Spring maize	61862.1	49114.4	15156.2
Double harvest areas	Laizhou	Winter wheat	80470.5	36737.9	10580.5
		Spring maize	55416.9	47502.9	19950.1
	Xinxiang	Winter wheat	67762.0	37375.3	9855.2
		Spring maize	44921.3	39932.5	14775.0
	Wuqiao	Winter wheat	75544.3	37724.4	10690.1
		Spring maize	41832.8	38705.3	12397.9
Triple harvest areas	Lianyungang	Winter wheat	66241.3	30095.8	9967.7
		Late rice	63510.4	54231.2	12994.5
	Wuxue	Early rice	41365.1	33569.3	10272.2
		Late rice	46688.9	44542.9	10356.7
	Jiangshan	Early rice	40973.0	32581.5	11133.1
		Late rice	52879.3	48753.3	11188.9
	Changsha	Spring maize	38358.4	28515.8	9743.9
		Late rice	49067.5	46351.7	10760.5
	Youxi	First season rice	57026.6	48933.0	14973.5
		Ratoon season rice	20860.2	19826.7	9516.8

of FY to TPP (SK_3) followed the same pattern as for SK_1.

Increasing potential yields in the short term in high-yielding regions

In the short-term, the potential increase in yield in the short term (SK_3-SK_2) sequence for the four crop types was the highest for maize (22.8%), followed by ratoon rice (20.4%), wheat (12.7%) and rice (11.1%). The potential increase in spring maize was lower than that for summer maize, with the spring maize proportional increase in the single harvest zone being higher than that in the triple harvest zone. The highest potential increase in spring maize was recorded in the Huadian region (36.8%) and in summer maize in the Wuqiao region (27.4%). First season rice had a lower proportional increase than ratoon season rice. Winter wheat in the double harvest zone was lower than in the triple harvest zone. In the double zone, the highest increase was recorded in Laizhou (13%). Early rice had a slightly higher proportional increase than late rice, with the highest proportion of early rice being recorded in the Jiangshan region (13.3%) and late rice in the Wuxue region (13.9%).

Increasing potential yields in the medium term in high-yielding regions

In the medium term, the potential increase in yield in the medium-term (SK_3-SK_1) sequence for the four crop types was highest for ratoon rice (44.9%), followed by maize (42.5%), wheat (27.1%) and rice (21.9%). The potential increase in first season rice was lower than that of ratoon season rice. Spring maize had a lower proportional increase than summer maize. The highest potential increase in spring maize and summer maize was recorded in the Huadian region (54.1%) and Laizhou region (57.9%) respectively. Winter wheat in the double harvest zone had a lower potential increase than in the triple harvest zone. In the double harvest zone, the highest potential increase was recorded in the Wuqiao region (30.4%). Late rice had a lower potential increase than early rice, with the highest increase recorded for early rice in the Jiangshan region (27.1%) and for late rice in the Wuxue (18.9%) region.

Discussion

Trends in RPP and its effect on crop growth and development

The 50-year RPP reconstructions for Northeast China indicate a downward trend (Figure 1). The Harbin region shows the steepest decrease, followed by Huadian and Haicheng regions. These results indicate that the hours of solar radiation have declined sharply in recent years, with the same results obtained for the percentage of solar radiation per hour. Radiation shows a gradual decrease for all regions of China, with a greater decrease with increasing latitude from south to north. Al-Ghouti et al. (2005) calculated a decrease of 8% in solar radiation compared with 9,000 years ago. The weather data for Sichuan indicated that, on average, there were 194 less hours of sunshine in the 1990s than in the 1950s, with a 5% decrease in the proportion of hours of sunshine. Fewer hours of solar radiation has had a noticeable impact on the growth and development of crops. Theoretical calculations by Bradford et al. (2006) indicated that the speed of photosynthesis decreases by 15% when the duration of solar radiation is shortened from 16 hours to 12 hours, under identical intensities of radiation (1,675 J cm^{-2}).

Trends in TPP and its effect on crop growth and development

In contrast, TPP values have remained relatively stable for the last few decades. During the last 100 years, the global average air temperature has increased by 0.6-0.8ºC (Frei and Gassner, 2008), with a recorded 0.55ºC rise in China. The average air temperature in China is forecast to increase by 1.7ºC in 2020 and 2030 and by 2.2ºC in 2050 (Tao and Zhang, 2011). At the same time, environmental conditions show a latitudinal increase in warmth from the south to the north (Nogués-Bravo et al., 2007). Higher temperatures accelerate the development of crops, reducing the growth stage. With every 1ºC rise in temperature, Porter and Gawith calculated a 7-8 day reduction in the number of days required to grow rice, and a 17-day reduction for wheat (Porter and Gawith, 1999). Over the last 10 years, the period of anthesis (during which a flower is open and fully functional) for 385 different plants has advanced by 4.5 days compared with 40 years ago, with 16% of plants noticeably advancing by 15 days in the 1990s (Alexandrova and Hoogenboomb, 2000). Hence, higher temperatures shorten the time required for photosynthesis, which leads to the accumulation of less dry matter, and in turn lower yields. In other words, fewer hours of solar radiation leads to a decline in RPP, while higher temperatures increase TPP. The system compensates to maintain stability in the photothermic resource, a mechanism which could be harnessed to enhance crop production.

Measurable indicators of theoretical yields

High yields arise as a result of a wide range of ecological factors, but are mainly affected by solar radiation and temperature, along with the cultivation technique used. In the study, the limiting ecological factor for winter wheat, spring maize and early rice was temperature, while the limiting ecological factor for summer maize, late rice and ratoon rice was radiation. Higher TPPE values indicated that the cultivation technique was suitable for the growth of local crops; the spring maize mode of production in the Huadian region and ratoon rice mode of production in the Youxi region should therefore be used as a reference for improving crop outputs in other regions. The theoretical yield calculated in the current study was generated from a combination of optimum ecological conditions and cultivation conditions. By increasing the efficiency of photothermal use and improving agricultural techniques, the calculated theoretical yield could be realized, and TPPE could be used as an indicator for predicting theoretical yields in different regions.

Changes in sowing area and grain yield in the short and medium term

In China between 1980 and 2003, the area of crop cultivation and main production zones declined sharply, except in the Northeast. Specifically, the total area of cultivation in 1980 was 116.47×10^6 hm^2, but had declined to 99.41×10^6 hm^2 in 2003 (Zhang, 2010). While the cultivation area increased in size between 2003 and 2006, currently only 106×10^6 hm^2 remains, which is far below the recorded area in 1980. The reasons for this rapid decline include the encroachment of urban development, reclaiming of land for the planting of grasses and

Table 3. Crop development in the short and medium term for four crops.

	Site	Crop type	SK_1 (%)	SK_2 (%)	SK_3 (%)	SK_3-SK_2 (%)	SK_3-SK_1 (%)
Single harvest areas	Harbin	Spring maize	66.1	49.9	23.7	26.3	42.5
	Huadian	Spring maize	90.9	64	36.8	27.2	54.1
	Haicheng	Spring maize	53.4	46.3	24.1	22.2	29.3
Double harvest areas	Laizhou	Winter wheat	54.3	42	29	13	25.3
		Summer maize	85.6	49.6	27.7	21.9	57.9
	Xinxiang	Winter wheat	46.9	38.8	27.8	11	19.1
		Summer maize	87.4	56.6	33.6	23	53.8
	Wuqiao	Winter wheat	59	35.6	28.6	7	30.4
		Summer maize	64.1	53.9	26.6	27.4	37.5
Triple harvest areas	Lianyungang	Winter wheat	64	50.3	30.4	19.9	33.6
		Late rice	46.1	35.2	28.5	6.7	17.6
	Wuxue	Early rice	56.5	40	31.1	8.9	25.4
		Late rice	45.2	40.3	26.3	13.9	18.9
	Jiangshan	Early rice	54.8	41.1	27.7	13.3	27.1
		Late rice	37.7	33.1	22.2	10.9	15.5
	Changsha	Spring maize	54.8	49.8	39.4	10.4	15.4
		Late rice	39.2	34	21.5	12.6	17.8
	Youxi	First season rice	58.2	38.5	21.7	16.8	36.5
		Ratoon season rice	97.6	68.3	44.4	23.9	53.2

Table 4. Cultivation techniques generating high yields in each region.

Technological patterns	Technological characteristics
High-yielding cultivation model with high density double-planting of summer maize	Uses varieties of short stalk and medium ear maize, with large and micro ridges and intensive cultivation (proposed by Denghai Li, Henan Academy of Agricultural Sciences, 2005; Kongjun Wang, Agricultural Institute of Shandong Agricultural University, 2005)
High-yielding model with cultivation in earth furrows for winter wheat	Crop canopies are in waves with planting in earth furrows, which increases the intake capacity per unit ear and improves canopy structure (proposed by Fahong Wang, Shandong Academy of Agricultural Sciences, 2005)
High-yielding cultivation model with high plant density in the ridges and boosted source capacity and sink capacity for rice	Ridge-cultivation technique with high plant density in wide rows, which optimizes the population structure, improves ventilation and light conditions, controls fertilizer use, strengthens root capacity and plant health, and generates a double-season of high yields in ears and grain (Xiufu Zhang, China National Rice Research Institute, 2005)
High-yielding technological model for ratoon rice	Simultaneous optimization of radiation and heat use which generates big spikes and strong roots in the first season to maximize formation of grain and rice stubs and accelerate growth (proposed by Yizhen Li, Fujian Academy of Agricultural Sciences, 2004)
High-yielding technological model employing nitrogen manipulation to delay senescence in winter wheat	Manipulation of nitrogen levels increases root activity, boosts plant health, keeps leaves green, delays senescence, increases dry matter accumulation and allocation of plant resources to spikes, achieves high photosynthetic efficiency and high harvest index (Zhenwen Yu, Shandong Agricultural University, 2005)
High-yielding technological model based on “four unifications” for winter wheat	Makes full use of predominance of the main stem, photosynthetic anti-resistance function of non-leaf green areas on the spike, stem and sheath and the continuous absorption capacity of primary roots, to achieve “the four unifications” of high yield, high efficiency, low consumption and simplification for winter wheat (Zhimin Wang, China Agricultural University, 2005)
High-yielding technological model with boosted sink capacity and source capacity for rice	Focuses on large spikes to boost the sink capacity, percentage of ear-bearing tillers and the ratio of grain to leaf to improve quality, and boost dry matter accumulation and the harvest index (Jianchang Yang, Yangzhou University, 2004)

Table 5. Increases in yield in the short and medium term.

	Site	Crop type	Sowing area (10^3 hm^2)	Short term increase (10^6 t)	Medium term increase (10^6 t)
Single harvest zones	Harbin of Heilongjiang	Spring maize	2457.2	13.57	21.94
	Huadian of Jilin	Spring maize	2805.7	14.67	29.17
	Haicheng of Liaoning	Spring maize	1900.3	10.48	13.82
	increment			38.72	64.93
Double harvest zones	Laizhou of Shandong	Winter wheat	3353.8	8.44	16.45
		Summer maize	2753.6	13.92	36.78
	Xinxiang of Henan	Winter wheat	5006.7	11.16	19.33
		Summer maize	2579.0	9.90	23.14
	Wuqiao of Hebei	Winter wheat	2417.2	2.79	12.19
		Summer maize	2658.1	13.17	18.04
	increment			59.38	125.93
Triple harvest zones	Lianyungang of Jiangsu	Winter wheat	1734.9	5.36	9.05
		Late rice	2230.8	4.22	11.05
	Wuxue of Hubei	Early rice	363.1	0.58	1.66
		Late rice	426.1	1.31	1.78
	Jiangshan of Zhejiang	Early rice	138.1	0.37	0.75
		Late rice	173.4	0.53	0.76
	Changsha of Hunan	Spring maize	268.5	0.48	0.71
		Late rice	1110.9	3.33	4.70
	Youxi of Fujian	First season rice	200.0	0.83	1.80
		Ratoon season rice	200.0	0.42	0.93
	increment			17.42	33.19

forests, and adjustments to agricultural practices. However, while the cultivation area for grain has declined in China, total yield appears to have increased. The national total yield increased from 318.22×10^6 t in 1980 to 497.48×10^6 t in 2006, a net increase of 179.26×10^6 t over the last 25 years. Yield has mainly risen in the provinces of Hebei, Shandong and Anhui, the Northeast region and the middle and lower reaches of Changjiang River, respectively. There remains a large gap between the four yield levels (Table 5). Hence, improving yields in moderate- and low-yielding fields is important. A noticeable increase in short-term yield is possible through an increase in technological and material input. Through better cultivation techniques, grain yield could increase by 38.72×10^6 t in the short term and 64.93×10^6 t in the medium term for single harvest areas in Northeast regions. In the double harvest areas of the Huai Hai Lyrics valley, these figures would be 59.38×10^6 t and 125.93×10^6 t for the short and medium term, respectively. For the triple harvest areas of the Yangtze River valley, these values would be 17.42×10^6 t and 33.19×10^6 t for the short and medium term, respectively.

Effect of cultivation technique on yield

The gap between FY and EAY is due to different crop varieties being grown in soil with different physicochemical characteristics. Therefore, the measures recommended in this section are to boost EAY. Firstly, new varieties with high yield and good quality crops should be identified through research, and introduced based on the local climatic and soil conditions. Crop varieties should be selected for their resistance and tolerance to high density planting, in addition to high yield and good quality produce. Secondly, ecological parameters should be incorporated into existing agricultural practices. Specific examples include conservation tillage, fertilization of land, increasing organic input, enhancing the favorable physical characteristics of soil, and employing techniques such as deep fertilization, all of which could improve the fertility of the sub-plough layer. Finally, field management and pest and associated disease prevention should be considered. For example, disease-resistant varieties should be selected, in parallel to the rational application of fertilizer and biological and chemical controls. Cultivation techniques that take full advantage of local photothermic resources are necessary to achieve the RY in the medium term. In recent years, high crop yields have been recorded in many parts of China. Table 4 lists the typical cultivation techniques used to achieve high yields in each region. TPP varies across regions, due to differences in climatic resources, and therefore cannot be altered by changing cultivation practices. For this reason, the current focus of scientific research in China is how to fully use photothermic resources to boost current high-yielding crops, such as through new density-tolerant crop varieties and cultivation techniques.

Materials and methods

Study locations

The regions of China generating the highest yields were selected for analysis (see Table 1)

Statistical analysis

Radiation production potential (RPP) and thermal production potential (TPP) were calculated according to the model put forward by Waddington (1986) and Long (1981) separately. They were represented by the following equations.

$$RPP = 3.75 \times 10^{-5} \times \Sigma Q \times \left(L_i / L_{\max}\right) \quad (1)$$

$$TPP = RPP \times f(t) = 3.75 \times 10^{-5} \times \Sigma Q \times \left(L_i / L_{\max}\right) \times f(t) \quad (2)$$

In the model, leaf area index ($L_i / L_{\max}$) and temperature ($f(t)$) were calibrated from the model put forward by Zhang et al. (2007) and Long (1980) separately. The economic yields of RPP and TPP were represented by the following equations.

$$Y_{RPP} = RPP \times HI = 3.75 \times 10^{-5} \times \Sigma Q \times \left(L_i / L_{\max}\right) \times HI \quad (3)$$

$$Y_{TPP} = TPP \times HI = 3.75 \times 10^{-5} \times \Sigma Q \times \left(L_i / L_{\max}\right) \times f\left(t\right) \times HI \quad (4)$$

According to the characteristic accumulation and allocation of dry matter, the values of harvest index (HI) for maize, wheat, rice and ratoon rice are 0.5, 0.48, 0.51 and 0.60, respectively.

Weather data source

The weather datasets were obtained from the weather station of the Yikangnong Company and the National Meteorological Information Center.

Conclusions

This study focused on the RPPE and TPPE of four crop types (maize, rice, ratoon rice and wheat) in the high-yielding regions of the Northeast plain, Huai Hai Lyrics valley and Yangtze River valley of China spanning a latitudinal range from N25.48° to N45.32°. The RPPE and TPPE varied with crop type, harvest zone and high-yielding areas. Compared with other types of crop, the RPPE and TPPE of ratoon rice (0.7406, 0.7848) were the highest; compared with the other regions, the RPPE of Youxi (0.7406) was the highest and TPPE of Youxi (0.7848) ranked second only to Huadian (0.9089). Compared with other crops in the triple harvest zone, the RPPE, TPPE, yield and theoretical yield of ratoon rice were the highest. Ratoon rice sprouts into axillary buds on the rice stub which remains after the rice is reaped, saving on costs and seeds in addition to boosting heat use efficiency and yield; this crop should thus be more widely grown across all regions. Temperature was the main limiting factor for winter wheat, spring maize and early rice while radiation was the main limiting factor for summer rice, late rice and ratoon rice, so optimizing the sowing date in the single harvest zone and rotation date in the double and triple harvest zones is important to obtain high yields.

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