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A Tale of Two Countries

Spatial and Temporal Patterns of Rice Productivity in China and Brazil

Liangzhi You

Environment and Production Technology Division

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

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INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
2033 K Street, NW
Washington, DC 20006-1002 USA
Tel.: +1-202-862-5600
Fax: +1-202-467-4439
Email: ifpri@cgiar.org

www.ifpri.org

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ABSTRACT

This paper examines differences in the spatial and temporal variations of rice yields in China and Brazil. Our analysis indicates that, in China, rice yields have converged over time and rice production has become increasingly homogeneous. In contrast, rice yields in Brazil have diverged over time, primarily due to variations in upland rice yields. Three hypothetical explanations may account for the different behaviors of rice yields in Brazil and China, namely: 1) differences in production systems (i.e. irrigated in China vs. upland in Brazil); 2) changes in rainfall patterns; and 3) bias in agricultural research and development (R&D) towards irrigated rice. Our empirical analysis supports the first two hypotheses by establishing that: 1) upland rice shows much more variation in yields compared to irrigated rice; and 2) changing rainfall patterns have primarily affected upland rice. We also provide evidence of the bias towards irrigated systems by looking at the patterns of varietal release.

Keywords: rice productivity, spatial convergence, technology spillover, China, Brazil

1. INTRODUCTION

Rice is widely produced and consumed in China and Brazil, and is a valued commodity in both countries[1]. Besides being a good source of calories[2], rice is also a source of employment and income for many farmers. Over the past few decades, these countries have invested significant efforts toward improving rice productivity and increasing production. Their efforts have largely paid off in terms of production and yields, to the point that China and Brazil together have accounted for roughly one third of the world's rice production since the 1960s. Such high levels of production make these two countries important and influential players in the world's rice market.

Increases in rice productivity have been the major source of production growth in both Brazil and China. The development and eventual adoption of high-yielding varieties (HYVs) during the Green Revolution played an important and significant role in this productivity improvement (Fan et al., 2005, Sanint, 2004). Rice yields increased 2.5 and 1.5 percent per year for China and Brazil, respectively, between 1970 and 2000. This rapid growth in productivity allowed China and Brazil to meet the growing demand for rice with little increase in planted area. The impacts of the Green Revolution on yields, however, were not uniformly distributed across rice-growing areas. In fact, significant variation can be observed across different rice ecologies, agroecological zones, demographic pressures and policy environments (Pingali, Hossain and Gerpacio, 1997, p.13). Increasing population growth and scarcity of land suitable for rice production suggest that China and Brazil need to further increase rice productivity if they hope to continue meeting the increasing demand for food. The search for new sources of productivity growth can be aided by improving our understanding of the spatio-temporal evolution of rice yield (Wood, You and Zhang, 2004).

Technology spillovers account for a significant share of agricultural productivity growth, and some studies suggest that research and development (R&D) spillovers might account for half or more of the total productivity growth (Alston, 2002). Given the generally easy access to agricultural technologies, technology latecomers may readily "catch up" simply by adopting existing technologies superior to their own (Wood, You and Zhang, 2004). This should be the case in particular for countries like China and Brazil, where agricultural extension services are relatively strong and effective. If the adoption of new and better technologies is indeed a simple process in China and Brazil, given the widespread dissemination of such technologies (through extension services) and the effects of spillovers, then we would expect crop yields to converge. Indeed, Goeschl and Swanson (2000) showed that crop yields in developing countries converged[3] to levels found in developed countries from 1961 to 1999 for most of the eight crops included in the study (barley, cotton, maize, millet, rice, sorghum, soybean and wheat). Using hybrid rice in India as an example, Zhang, Fan and Cai (2002) showed that early successful HYV adopters had a large effect on neighboring farmers, which translated into higher technological adoption by other farmers. This suggests that technological spillover is the centripetal force for productivity convergence. However, the impact of agricultural technology is usually quite location-specific. Crop production is subject to substantial spatial heterogeneity in terms of soil, terrain and climate, which can impede technological transfer and adoption. This is the centrifugal force for crop yield convergence. Wood, You and Zhang (2004) showed that maize, rice and soybean yields in Latin America and the Caribbean did not converge between 1975 and 1998. Given the variability of yields across production systems, crops and regions, as well as the lack of consensus from previous studies, the issue of crop yield convergence over time and space remains largely an empirical question.

Although a large body of literature deals with technology adoption and transfer, most of these studies focus on a micro scale and few have investigated the spatial patterns of technology spillover on a country/industry-wide scale, primarily due to data limitations (Wood, You and Zhang, 2004; Cabrer-

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[1] The per capita consumption of white rice in Brazil is approximately 54 kilos per year (Velásquez, Sanint and Teixeira, 1991).

[2] In 2000, rice accounted for 40 percent of the total calorie intake in China and 12 percent in Brazil.

[3] The authors found evidence of absolute convergence.

Borras and Serrano-Domingo, 2007). Using a panel dataset of rice yields in China and Brazil, the present paper fills this analytical gap by examining spatial patterns of rice yield variation and variability on a country-wide scale. Our analysis is divided into three stages: 1) Panel data analysis is used to document the spatio-temporal changes for rice yields. 2) Tests for yield convergence in the two countries are applied; the results suggest convergence for China but not for Brazil. 3) Given that yields converged for China but not for Brazil, we use the Shorrock inequality decomposition method and Geographic Information System (GIS) tools to analyze the underlying causes of the differences observed between the two countries.

Three hypotheses are offered to explain the differences in rice yield convergence in the two studied countries:

1. Differences in rice production systems: The majority of rice in China is irrigated, whereas that in Brazil is produced in a combination of irrigated and upland ecologies. We hypothesize that these differences in production systems contribute to the yield divergence in Brazil.
2. Impact of climate change, particularly in the context of changing rainfall patterns: Rainfall patterns have changed over the past few decades due to climate change. Increasing rainfall variability has exacerbated yield divergence in rainfed areas, thereby affecting rainfed rice production, which relies on consistent rainfall during the growing season.
3. Agricultural R&D bias towards irrigated areas: International and domestic investments in agricultural R&D over the past few decades have been heavily biased towards irrigated production systems. This bias benefits irrigated rice more than rainfed rice. We believe that the divergence in yields in Brazil is derived primarily from the variability in upland rice yields.

The remainder of this paper is organized as follows. We first describe the panel dataset and rice production systems in Brazil and China. Next, we analyze temporal and spatial yield variabilities in China and Brazil. The final section investigates the underlying causes for the differences in rice productivity convergence between these two countries. We conclude with a summary and some policy implications.

2. DATA AND RICE PRODUCTION SYSTEMS

We compiled time-series data of rice production statistics (production, area and yield) at the county level for China and at the municipality (município) level for Brazil[4]. The time series runs from 1980 to 2000 for China and from 1975 to 2000 for Brazil. During this period, rice was produced in approximately 2,300 counties in China and 3,800 municipalities in Brazil, which corresponds to 95 percent of all Chinese counties and 85% of all Brazilian municipalities. Two GIS boundary files for Chinese counties and Brazil municipalities were linked to the corresponding statistical data. In addition, we calculated average rainfall[5] during the rice-growing season for all counties in China from 1980 to 2000 and for all municipalities in Brazil from 1975 to 2000. The county/municipality rainfall measures were calculated by averaging the rainfall values of all pixels within the counties/municipalities. Annual rainfall measures were taken as the averages of monthly rainfall, thus accounting for changes in the growing seasons across the counties/municipalities in China and Brazil.

During the study period, rice was grown via three different production systems in China and Brazil: irrigated lowland, rainfed lowland, and upland. The utilized production system impacts rice performance, and fundamental differences in plant characteristics and physiology make particular types of rice more or less suited to different production systems. For example, the modern semi-dwarf, high-yielding varieties developed during the Green Revolution for the irrigated and favorable rainfed lowland systems could not be grown in upland systems. In China, irrigated rice was the primary rice production system, accounting for over 93 percent of total area sown to rice. Rainfed lowland rice and upland rice accounted for 5 percent and 2 percent of the remaining area, respectively. Upland rice was typically found in provinces that have mountainous regions, such as in Yunnan, Guizhou, Guanzi, and Jiangxi. Rainfed lowland rice was mainly planted in water-limited areas, such as those found in the provinces of Hebei, Henan, Shangdong, Shaaxi, and Liaoning (see Figure B.1 for a map on rice production systems in China). In Brazil, about one-third of the area planted with rice was irrigated. The remaining two-thirds were predominantly cultivated under upland systems, with only a small percentage grown under rainfed lowland systems. As shown in Figure B.2, almost all rice in Santa Catarina and Rio Grande do Sul was irrigated. A few other states such as Tocantins, São Paulo, and Mato Grosso do Sul produced limited amounts of irrigated rice. Rainfed lowland rice was grown in only three states: Sergipe, Minas Gerais and Rio de Janeiro.

Since relatively little of rice area in China and Brazil was rainfed lowland, we would herein focus on irrigated and upland rice.

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[4] The Brazilian data come from Embrapa (Empresa Brasileira de Pesquisa Agropecuária; the Brazilian Agricultural Research Cooperation). The Chinese data come from the Ministry of Agriculture and the Chinese Academy of Agricultural Sciences (CAAS).

[5] Rainfall data were obtained from the Climate Research Unit at University of East Anglia. We utilized the CRU TS 2.0 dataset, which is a 0.5-degree latitude/longitude-gridded dataset of monthly worldwide rainfall for the period 1901-2000 (Mitchell et al. 2006).

3. SPATIAL AND TEMPORAL PATTERNS OF RICE YIELD

Figure 1a. Spatial change of rice yield in China, 1980-2000

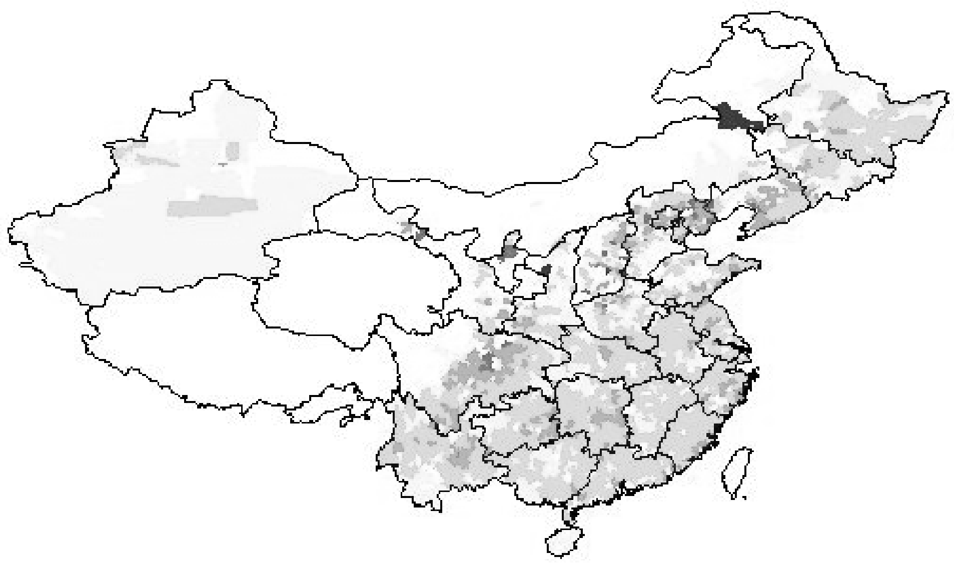


Figure 1b. Spatial change of rice yield in China, 1998-2000

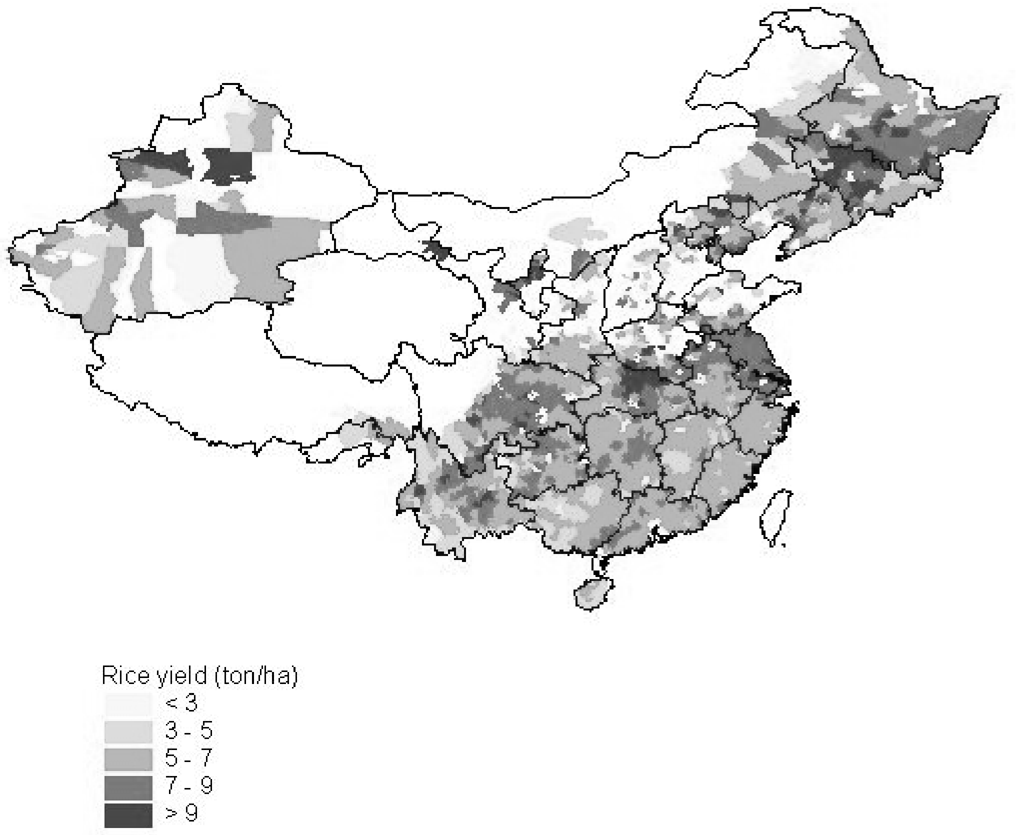
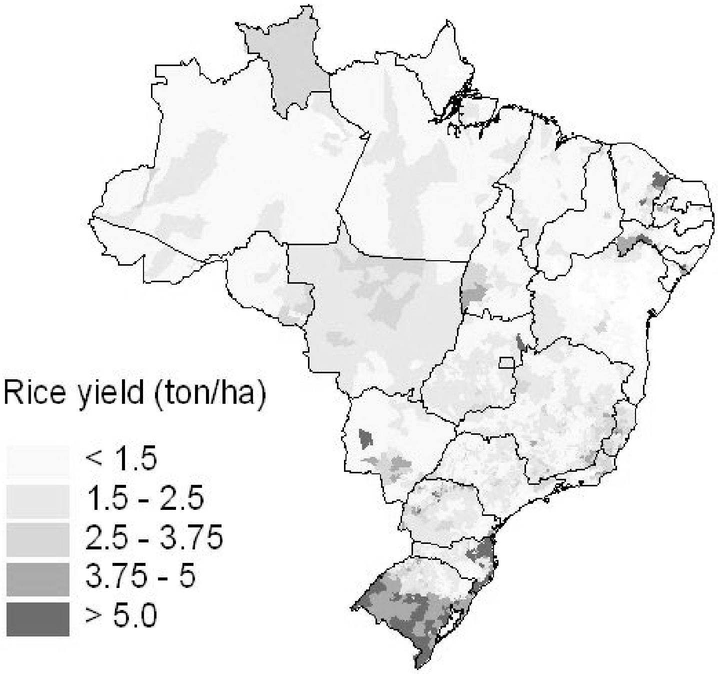


Figure 2a. Spatial change of rice yield in Brazil, 1975-77

Figure 2b. Spatial change of rice yield in Brazil, 1998-00



Figures 1 and 2 show the spatial changes in rice yield[6] over the past two decades in China and Brazil, providing snapshots of spatial yield variation at the start and end years of the examined period. Two specific patterns emerge from these maps. First, there is significant spatial variation of rice yields in China and Brazil, which suggest that an analysis based on national averages would miss a great deal of the relevant spatial variation in yield performance. For instance, rice yields in the Northern China Plain and Xingjing province averaged about 3 ton/ha in 2000, while those in Northeast China were considerably higher, averaging over 7 ton/ha. Likewise, in Brazil, highly productive states such as Santa Catarina and Rio Grande do Sul saw an average yield of 5 ton/ha, whereas other states like Amazona and Mato Grosso performed considerably poorer, with yields averaging 1.5 ton/ha.

Second, although there is considerable spatial heterogeneity in yield performance, we see a general upward trend in rice yields for Brazil (1975 to 2000) and China (1980 to 2000). In China, the largest yield gains occurred in the Northeast region and the province of Xinjiang. In Brazil, the areas with largest yield increases included states such as Roraima, Mato Grosso, and Minas Gerais, whereas Santa Catarina and Rio Grande do Sul saw limited yield gains during the same period. Comparison of Figures 1(a) and (b) reveals an apparent expansion in area sown to rice from 1980 to 2000 in Northeast China, Inner Mongolia and the Sichuan provinces. Similarly, comparison of Figures 2(a) and (b) provides evidence that the rice area expanded into the Brazilian savannas, or “cerrados.” Most of the non-rice-producing savannas in 1970s were planted to rice in 2000, particularly those in the states of Amazonas, Rondônia, Mato Grosso, and Bahia. Indeed, upland rice cultivation has played a crucial role in bringing the Brazilian savannas under cultivation, as the low fertility and acidic soils of the region has limited the cultivation of other crops (Pinheiro, Castro and Guimarães, 2006).

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[6] We took three-year averages of yields to avoid atypical years due to natural disasters.

Figure 3a. Rice yield distribution in China, 1980-82

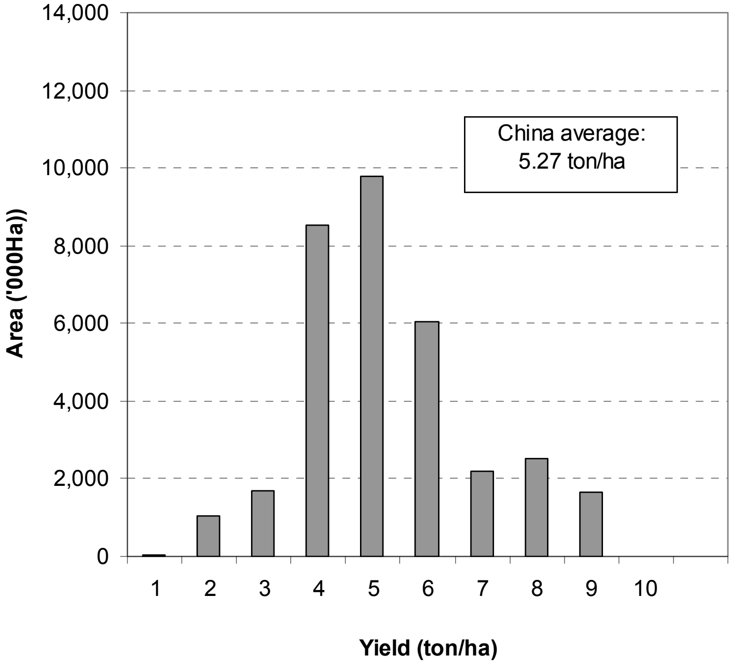


Figure 3b. Rice yield distribution in China, 1998-00

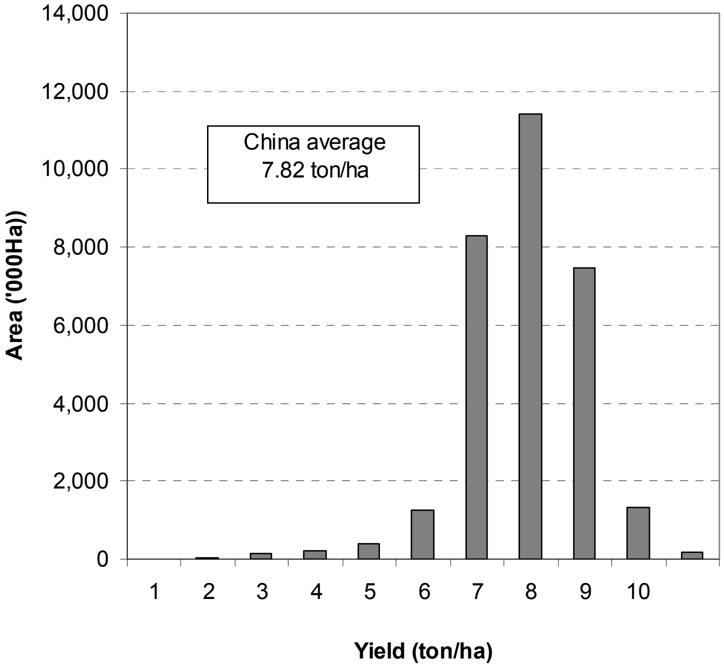


Figure 4a. Rice yield distribution in Brazil, 1975-77

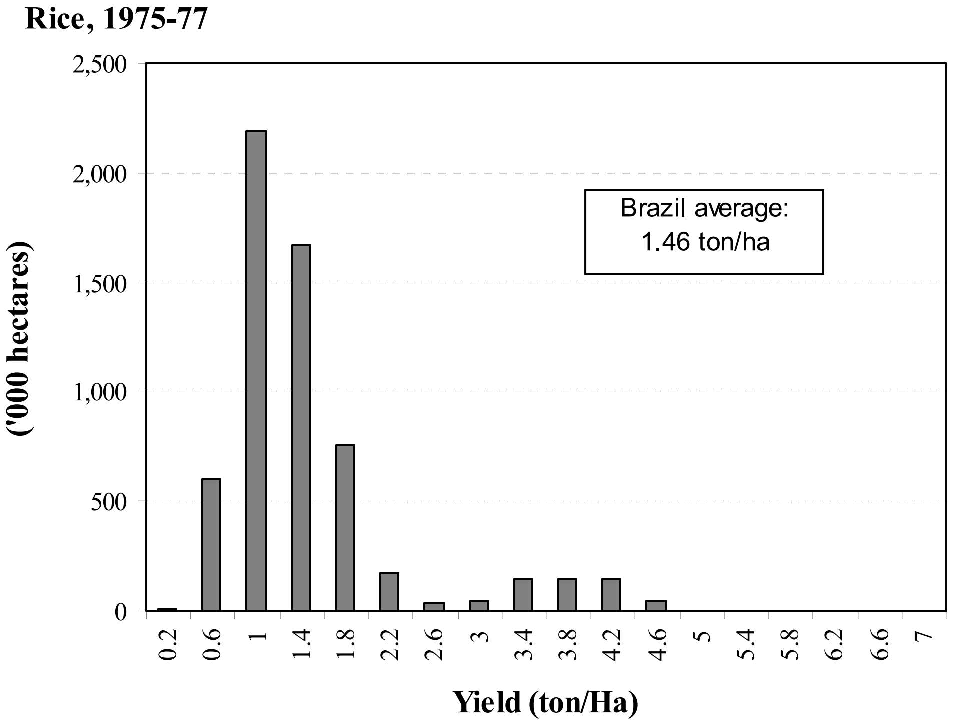
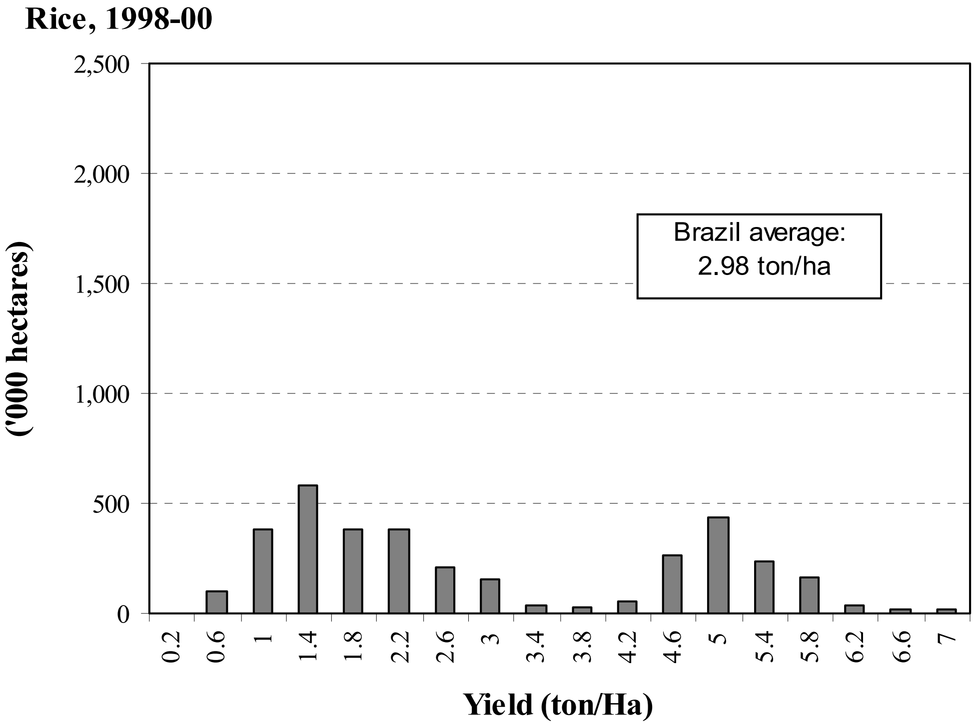
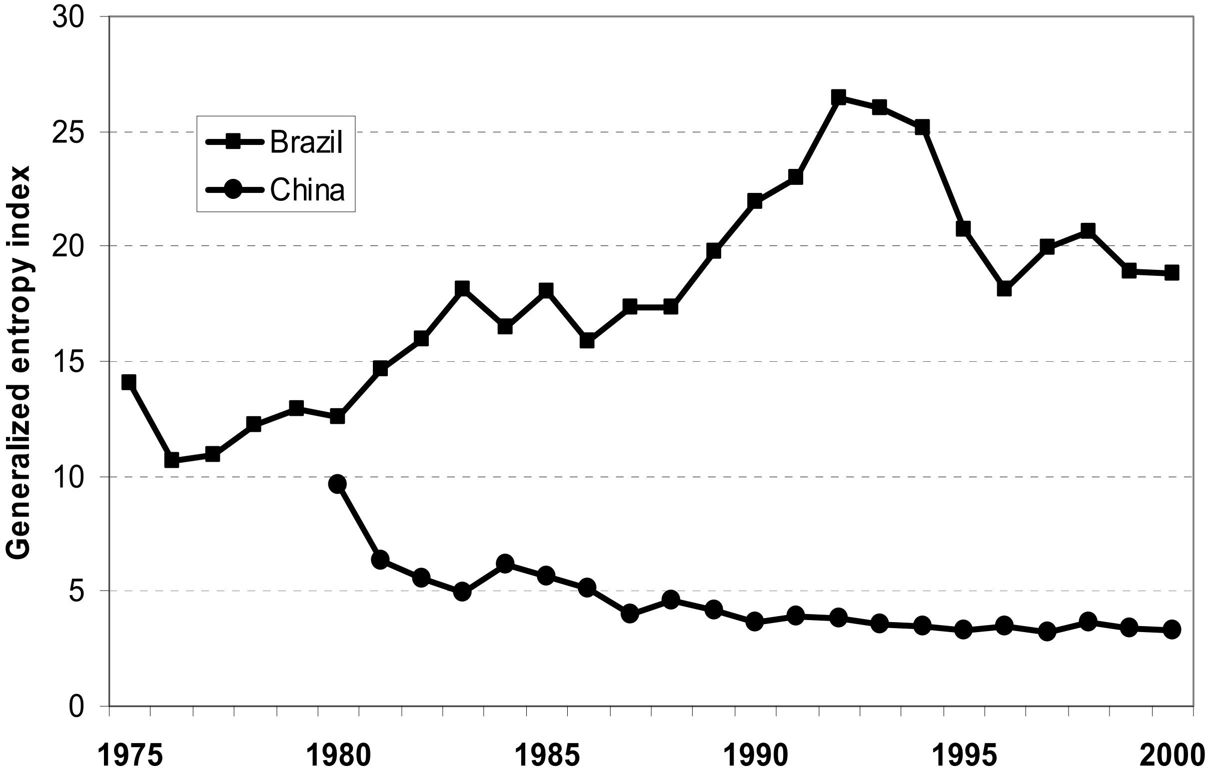


Figure 4b. Rice yield distribution in Brazil, 1998-00



A more quantitative sense of rice yield changes may be gained from Figures 3 and 4, which show the yield distribution at the county (for China) and municipality (for Brazil) levels. These histograms of yield distribution are plots of the harvested area within each yield class, and represent about 2,300 counties in China and 3,800 municipalities in Brazil. We can see that the yield distribution in China (Figure 3) moves to the right and the range becomes narrower from 1980 to 2000, indicating that Chinese rice yields both increased and converged during this period. However, the case is rather different in Brazil. On average, Brazilian rice yields also increased, from 1.46 ton/ha in 1970s to 2.98 ton/ha in the late 1990s (compare Figures 4(a) and (b)). However, the rice yields in Brazil for this period show a bimodal distribution, reflecting the two distinct rice production systems used in this country: the first clustering of rice area in the range of 0.6 to 2.6 ton/ha presumably represents rice grown under the upland system, while that in the 4.6 to 6.2 ton/ha (3.4 to 4.6 ton/ha in Figure 4(a)) range most likely represents irrigated rice. The bimodal distribution implies that yield growth has not been uniform across the two production systems utilized in Brazil. This disparity in growth trends and levels (note the larger yield range in Figure 4(b) compared to Figure 4(a)) suggests that yields have diverged rather than converging in Brazil.

Figure 5. Spatial variability of rice yields in China and Brazil



To further investigate the spatial variability of rice yields and gain a better understanding of the differences in yield patterns between China and Brazil, we used the decomposable generalized entropy[7] (GE) class of inequality measures developed by Shorrocks (1980, 1984). The GE index, which measures the overall spatial variability of yields, can also be decomposed into sample groups, in order to assess the contribution of individual groups to total variability and the variability within and between groups (Kanbur and Zhang, 2005). Figure 5 shows spatial variations of rice yield in China and Brazil from 1975

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[7] Please see Appendix A for technical details.

to 2000, revealing a much higher spatial variability in Brazilian yields compared to Chinese yields. This apparent difference in the levels of variability is confirmed by the results of the GE analysis. The GE index of rice yields for China shows a gradual decline of 4% per year from 1980 to 2000, with small peaks in 1984 and 1988. In contrast, the GE index for Brazil increases by 4.5% per year from 1975 to1993 and gradually decreases thereafter. These results confirm our finding that rice yields converged in China but not Brazil from 1980 to 2000.

4. UNDERLYING CAUSES

Since the observed patterns of rice yield variability in Brazil and China seem to conflict with one another, we investigated the underlying causes for these trends. As outlined in the introduction, we propose three hypotheses to explain the observed differences in the temporal-spatial patterns of rice yield variability, as described in detail below.

Table 1a. Spatial variability of rice yield, China (1980-2000).

Year	Generalized Entropy Index				Polarization Index(%)
	Total	Upland	Irrigated	Between	
1980	9.15	11.70	9.15	0.09	1.01
1981	6.20	6.96	6.14	0.06	0.91
1982	5.49	5.23	5.44	0.05	0.88
1983	4.78	4.95	4.72	0.06	1.23
1984	6.10	4.80	6.04	0.06	0.97
1985	5.62	4.40	5.58	0.05	0.86
1986	4.87	6.34	4.79	0.07	1.45
1987	3.91	2.61	3.85	0.07	1.67
1988	4.58	3.04	4.52	0.07	1.56
1989	3.88	5.90	3.81	0.06	1.63
1990	3.61	2.22	3.56	0.05	1.50
1991	3.80	3.82	3.75	0.05	1.40
1992	3.63	3.95	3.56	0.07	1.81
1993	3.38	4.86	3.32	0.06	1.77
1994	3.37	3.28	3.33	0.04	1.26
1995	3.19	3.00	3.15	0.04	1.17
1996	3.24	4.50	3.08	0.11	3.39
1997	3.19	2.38	3.14	0.05	1.51
1998	3.30	4.40	3.27	0.10	3.03
1999	3.20	3.40	3.13	0.08	2.50
2000	3.10	2.60	3.10	0.07	2.26

Table 1b. Spatial variability of rice yield, Brazil (1975-2000).

Year	Generalized Entropy Index				Polarization Index(%)
	Total	Upland	Irrigated	Between	
1975	14.05	7.94	11.93	5.56	39.59
1976	10.68	5.35	11.34	4.55	42.64
1977	10.92	5.21	10.40	4.97	45.52
1978	12.22	5.50	13.83	5.46	44.67
1979	12.94	6.10	13.45	5.79	44.72
1980	12.55	5.84	12.79	5.71	45.53
1981	14.64	7.53	11.37	6.53	44.65
1982	15.92	7.65	13.45	7.32	46.00
1983	18.09	9.63	13.57	7.71	42.64
1984	16.49	7.42	13.75	7.80	47.32
1985	18.00	8.38	13.06	8.59	47.71
1986	15.87	7.11	13.75	7.46	46.99
1987	17.33	8.92	12.66	7.68	44.30
1988	17.37	8.67	12.80	7.88	45.35
1989	19.79	10.46	11.63	9.08	45.87
1990	21.95	12.15	9.46	10.42	47.46
1991	22.98	12.40	7.39	11.77	51.23
1992	26.41	14.50	8.85	13.25	50.16
1993	26.03	14.29	7.44	13.55	52.05
1994	25.16	14.52	6.51	12.75	50.67
1995	20.75	10.92	6.08	11.12	53.60
1996	18.10	8.89	4.59	10.58	58.44
1997	19.90	10.74	4.43	11.22	56.37
1998	20.63	13.31	3.82	10.57	51.24
1999	18.93	11.80	3.63	9.75	51.51
2000	18.80	11.84	3.54	9.67	51.45

Figure 6a. Spatial variability of rice yield in China, 1980-2000

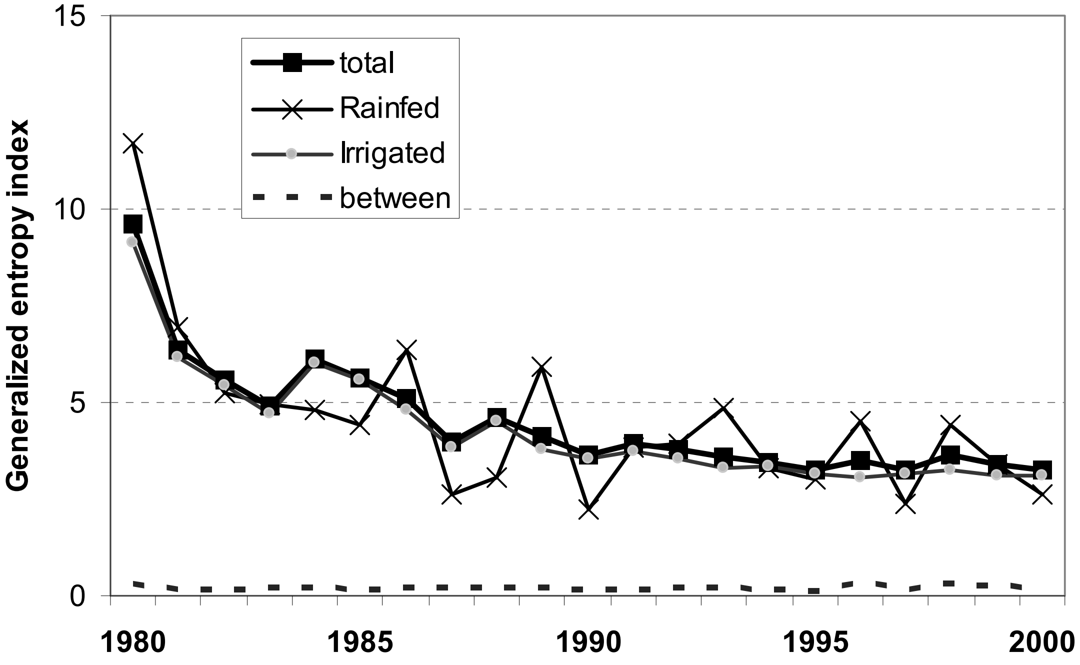
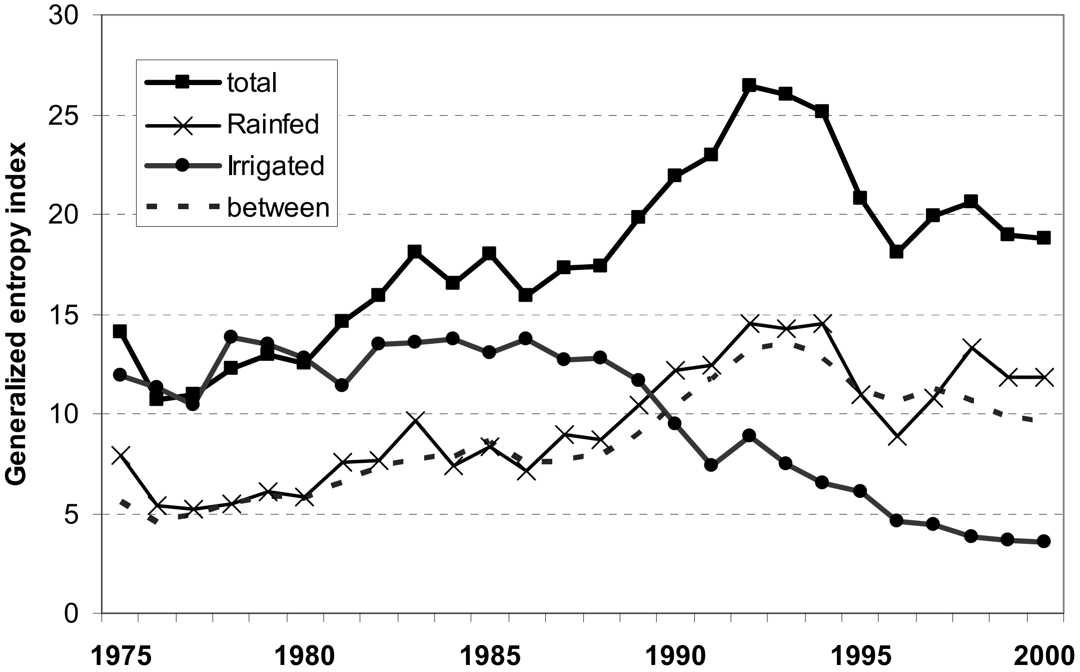


Figure 6b. Spatial variability of rice yield in Brazil, 1975-2000



Differences in Production Systems

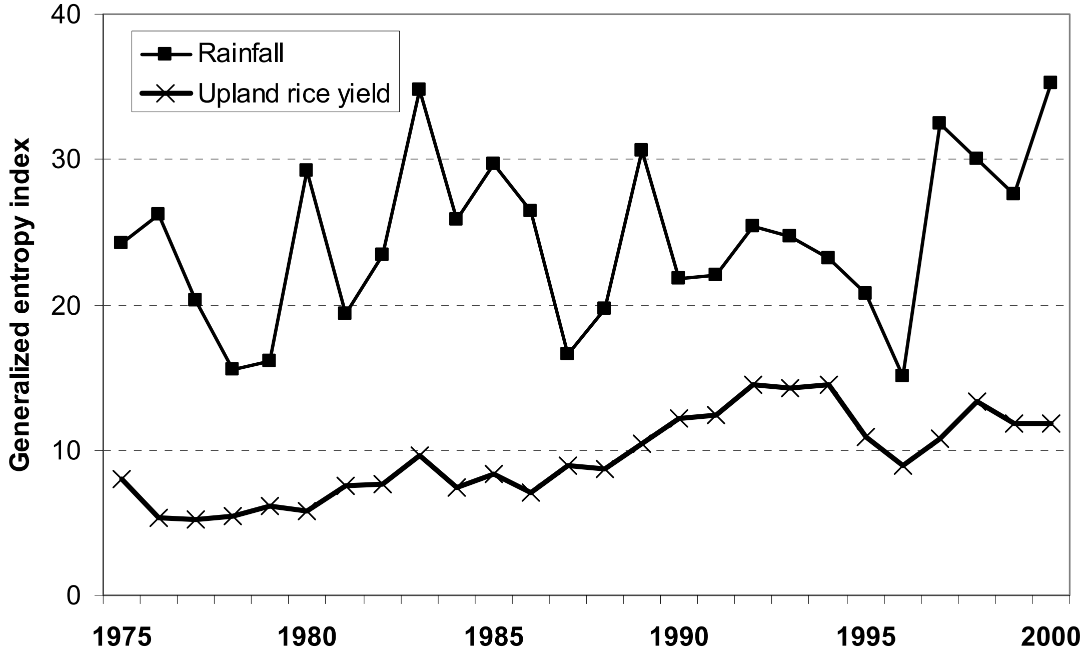
As mentioned above, rice yields depend largely on the utilized production system, particularly the ability of the system to provide a reliable water supply. Irrigated rice achieves much higher yields because it has constant access to water during the growing season. In contrast, upland rice, which relies on rainfall for water, may suffer crop damage if the required rainfall does not come during the critical growing period. The average upland rice yield in Brazil was only 25 percent that for irrigated rice in 2000. In addition, most of the irrigated rice plots in China and Brazil were characterized by more favorable biophysical (soil) and socio-economic (e.g. market access) conditions than the upland rice plots. These differences in conditions (whether biophysical or socio-economic) may help explain why irrigated rice not only has a much higher yield than upland rice, but also shows a more homogeneous pattern of yield growth. Rice in China was over 90 percent irrigated while almost two-thirds of the rice grown in Brazil was cultivated under an upland regime during the study period. We therefore hypothesized that the spatial variability of rice yields in Brazil comes mainly from the yield variability in upland rice. To verify our hypothesis, we used Shorrock's decomposition method to quantify the relative contributions of upland and irrigated rice to the overall spatial variability. Table 1 and Figure 6 give the spatial variations for both Chinese and Brazilian rice yields. The table shows generalized entropy indices for total rice, irrigated rice and upland rice, the index between irrigated and upland rice, and the polarization index (see Appendix A for definitions). This analysis reveals that the spatial variability of Chinese yields decreased from 1980 to 2000 primarily due to the decreasing variability of irrigated rice. The spatial variability of upland rice in China maintained an overall decreasing trend with considerable yearly fluctuations, while the variability between upland and irrigated rice remained small and similar (around 0.08). The polarization index increased from 1% in 1980 to over 2% in 2000, due to declines in the total variation index over the period (Table 1(a) and Figure 6(a)). Because rice was dominantly irrigated in China and the spatial variability of irrigated rice declined over the study period, the fluctuating variation of upland rice and increasing polarization between irrigated and upland rice had little impact on total rice variation in China.

In contrast to the declining yield variation in China, the GE index of rice yield in Brazil increased from 14.05 in 1975 to almost 18.80 in 2000, a 36 percent increase. The increasing total variability arose mainly from the increasing variability of upland rice (from 7.94 in 1975 to 11.84 in 2000) and the increasing variability between irrigated and upland rice (from 5.56 in 1975 to 9.67 in 2000); these represented increases of 51 and 75 percent, respectively. The spatial variability of irrigated rice in Brazil fluctuated between 12 and 14 from 1975 to 1983, but thereafter decreased between 1984 and 2000 (Table 1(b) and Figure 6(b)). Across the entire study period of 1975 to 2000, the GE index of irrigated rice in Brazil decreased by 70%. These results show that the increasing variability in Brazilian rice yields could be mainly ascribed to an increasing yield variability in upland rice and an increasing polarization between irrigated and upland rice.

The Impact of Climate Change and Particularly Changing Rainfall Patterns

Since crop production is intrinsically location-specific, we hypothesize that differences in local resource endowments could contribute to the spatial difference of crop yields. Large countries such as China and Brazil tend to have significant climate variability, which could be seen as a factor affecting crop yield variability. Many case studies have shown that crop yields are affected by increasing climate variability and global warming, both of which are consequences of climate change (for example see Nichalls, 1997; Carter and Zhang, 1998; Naylor et al. 2002; Lobell and Asner, 2003; Peng et al. 2004; Wang and You, 2004; You et al. 2005). Rainfall is the most important climate factor for rice production, particularly for non-irrigated rice. We therefore examined whether changes in rainfall patterns over the past few decades have impacted the spatio-temporal pattern of rice yields in Brazil and China.

Figure 7. Spatial variability in rainfall and upland rice yield in Brazil



Not surprisingly, annual rainfall during the rice-growing season has negligible impact on irrigated rice yields, because irrigation can compensate for any rainfall shortages[8]. This is true for both China and Brazil. However, our analysis indicates that changes in rainfall patterns affected upland rice yields, as seen when we plot the spatial variability of rainfall and upland rice yields in Brazil (Figure 7)[9]. Three features of Figure 7 are worth noting: First, the spatial variability of rainfall was two to three times higher that of upland rice yields in Brazil, and the yearly variation of rainfall variability was higher than that of the corresponding rice yields. Second, we see a small but statistically significant upward trend in rainfall variability (a slope of 0.21 per year for rainfall GE indices, with *t*-value -3.57), but this upward trend in rainfall is smaller than the corresponding upward trend in upland rice yield variability (a slope of 0.31 with *t*-value -4.57). Third, we observe some joint movement between upland rice yield indices and rainfall indices, with the rainfall and rice yield indices both increasing from 1987 to 1989, and then suddenly dropping in 1996. This supports our hypothesis that changing rainfall patterns may have contributed to the increasing yield divergence in upland rice production. Indeed, growing evidence suggests that rainfall variability and extreme events such as drought and floods have increased over the past few decades (Dai, Fung and Genio 1997, Dai, Trenberth and Qian 2004, Chen et al. 2004).

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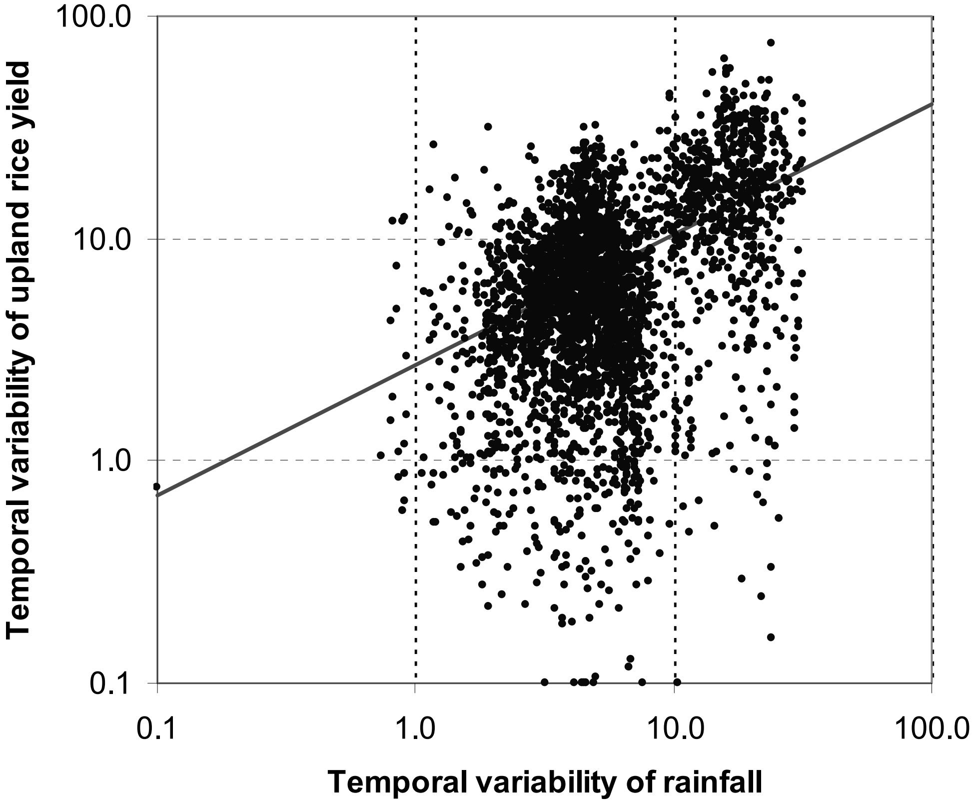
[8] However, rainfall affects the availability of irrigation water, especially under extreme climate conditions such as drought.

9 There was limited upland rice production in China, meaning that too few observations were available for meaningful spatial variability estimation in this country.

Figure 8. Temporal variability in rainfall and upland rice yield in Brazil



To examine the covariate patterns of temporal variability of rainfall and rice yield for Brazil, we calculated the temporal variability in upland rice yields and the average rainfall for the Brazilian municipalities. Figure 8, which shows the temporal variation in rainfall and upland rice yield in Brazil, reveals an apparent correlation between the variability of rainfall and upland rice yields, with a R^2 value of 0.5. This correlation of temporal variability suggests that increasing rainfall variability from 1975 to 2000 contributed to the increasing divergence of upland rice yields in Brazil.

Agricultural R&D Bias towards Irrigated Areas

This bias appears to have two main aspects: first, there is a much higher investment in breeding and extension services for irrigated rice varieties; and second, the potential for technological spillovers is greater for the relatively more homogenous irrigated areas compared to the upland areas, which tend to be agro-ecologically heterogeneous (Wood, You and Zhang, 2004). High-yielding varieties (HYVs) developed during the Green Revolution were targeted towards tropical and subtropical regions with good irrigation systems or consistent rainfall (Evanson and Gollin 2003). Sanint and Wood (1998) showed that almost 90 percent of the new rice varieties released in Latin American and the Caribbean (LAC) since the 1970s were targeted toward irrigated and rainfed wetland production environments.

Table 2. Rice production by seed varieties in irrigated and upland areas in Brazil.

Year	Areas Under Modern Semi-dwarfs				Rice yield (ton/ha)			
	Upland		Irrigated		Upland		Irrigated	
	(1000ha)	(%)[a]		(%)[a]	Traditional[b]	MSV[b]	Traditional	MSV
1975	0.0	0.0	0.0	0.0	1.26		3.60	
1976	0.0	0.0	10.9	2.0	1.27		3.60	4.30
1977	0.0	0.0	22.5	4.0	1.27		3.70	4.30
1978	101.8	2.0	37.4	7.0	1.02	1.50	3.80	4.50
1979	246.5	5.0	41.8	8.0	1.11	1.50	3.85	4.50
1980	395.5	7.0	53.4	9.0	1.30	1.50	3.90	4.70
1981	439.4	8.0	61.0	10.0	1.06	1.00	3.90	5.23
1982	443.2	8.2	248.1	40.0	1.28	1.70	3.90	4.70
1983	375.8	8.4	380.4	60.0	1.06	1.70	3.90	4.70
1984	393.6	8.5	468.7	65.0	1.22	1.70	3.90	4.70
1985	363.1	9.0	576.3	80.0	1.38	1.90	3.90	4.70
1986	418.3	9.3	994.3	91.0	1.10	1.90	3.90	4.75
1987	456.7	9.4	1050.6	92.0	0.95	1.90	4.00	4.75
1988	461.5	9.8	1157.9	92.5	1.18	2.00	4.00	4.75
1989	420.2	10.2	1156.0	93.0	1.10	2.30	4.30	4.87
1990	368.8	12.0	1024.7	93.2	0.42	2.30	4.00	5.00
1991	397.6	13.0	1094.3	93.4	1.02	2.50	4.00	5.00
1992	483.2	14.0	1149.9	93.6	0.93	2.30	4.20	5.00
1993	484.5	15.0	1257.9	93.8	0.82	2.30	4.20	5.10
1994	535.0	17.0	1217.3	94.0	1.05	2.30	4.20	5.10
1995	497.3	16.1	1192.0	92.2	0.95	2.30	4.30	5.20
1996	555.3	20.0	1083.8	95.0	1.32	2.10	4.30	5.20
1997	494.6	21.0	1193.3	96.0	1.09	2.00	4.20	5.10

(a) Percent area planted to Modern Semi-dwarf Variety (MSV). MSV is equivalent to high-yielding varieties (HYVs).
(b) Rice yield using traditional or MSV seeds.
(c) Source: EMBRAPA (Brazilian Agricultural Research Corporation).

China's rice breeding programs[10] almost exclusively focus on irrigated rice varieties, which has translated into high adoption rates of these varieties. Few Chinese breeding programs work with upland and rainfed lowland rice ecosystems, meaning that these varieties are typically introduced from other countries (Zhu, 2000). In contrast, Brazil, has a vast upland rice area, and benefits from the Upland Rice and Bean Research Center (CNPAF), which was established in 1974 and released a total of 35 new varieties from 1976 to 2000 (Pardey et al. 2006). Even with such a dedicated institute for upland rice, however, the adoption of modern upland rice varieties is still low in Brazil. Table 2 shows the changes in area and yield for rice by seed variety from 1975 to 1997 in Brazil[11]. The area planted in modern semi-dwarf irrigated rice varieties increased from zero in 1975 to almost 1.2 million hectares in 1997, when over 96 percent of the irrigated rice planted in Brazil originated from HYVs. The adoption rates of HYV

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[10] China has also pioneered the development of hybrid rice varieties and was the first country to commercially use them. Hybrid rice alone accounted for over 60% of total rice production in 1990s (Fan et al. 2005).

[11] This is the latest year for which data were available.

for upland rice were considerably lower than those for irrigated rice, but the level of adoption was still significant, with approximately 21 percent of the area planted with upland rice sown to HYVs in 1997. While the adoption rates were lower for upland versus irrigated rice, the change in HYV use over time was quite impressive, from nearly zero in 1975 to almost 500,000 hectares in 1997. The difference in adoption rates of irrigated versus upland rice HYVs is reflected in yield performance, as established in the previous sections. The benefits of HYVs, however, go well beyond higher productivities, as they may reduce yield variability and can be tailored to deal with pests and other constraints (e.g. drought).

In summary, the observed differences in the performance levels of irrigated versus upland rice, differences in the adoption rates of HYVs, and the differences in rice production systems between Brazil and China appear to collectively explain why yields have not converged in Brazil as they have in China.

5. CONCLUSIONS

We herein examine and compare the spatial and temporal patterns of rice yield variability in China and Brazil. Our analysis shows that rice yields in China have converged while those in Brazil have diverged over time. Further examination indicates that the underlying causes for the differences in yield variability between Brazil and China appear to include differences in the rice production systems of China and Brazil (particularly the fact that upland rice production dominate in Brazil), changes in rainfall patterns over time, and the technology bias towards irrigated rice production environments.

The rice production systems utilized in China and Brazil are a significant factor in the observed differences of their rice yield patterns. Irrigation reduces much of the yield variability in areas where irrigation has replaced rainfed production. China's use of primarily irrigated rice production, along with the technological bias toward technologies applicable for more favored production systems and the wide adoption of modern high yield varieties, have contributed to the convergence of overall rice yields in China over the past few decades. In Brazil, the mixed nature of the rice production systems (one-third irrigated and two-thirds upland) is a major factor underlying the observed rice yield divergence over time. As in China, irrigated rice yields in Brazil converged over the study period. However, upland rice yields diverged, and the polarization between irrigated and upland rice increased. The increasing spatial variability of upland rice in Brazil has been affected by recent changes in rainfall patterns. The statistically significant correlation between temporal variability of upland rice yields and that of rainfall suggests that changing climate regimes have affected the patterns of upland rice yield performance. The agricultural R&D bias against upland rice has further contributed to the increasing divergence of upland rice yields.

The difference in convergence or divergence of yield trends in Brazil and China provides us with some valuable lessons. Agricultural R&D investments in China and Brazil, as in the rest of the world, have focused on favored areas of research, meaning that irrigated rice has received considerably more attention than upland rice. Providing systematic irrigation is considerably more expensive than rainfall-dependent production systems. Thus, focusing research on irrigated rice as opposed to upland may also have had a distributional effect, favoring farmers in better financial situations who are likely to have better lands. If this is the case, we can frame the differences between irrigated and upland rice systems in the context of favored versus less favored areas. In recent years, researchers have examined the impacts of investing in less-favored areas and have found that (rates of economic) returns can be quite high and have the additional benefit of reducing poverty (Fan and Hazell 1999). Anecdotal evidence also suggests that investments in less-favored areas may reduce resource and environmental degradation while promoting economic growth and poverty reduction. Thus, increased investment in technologies, infrastructure and institutions targeting less-favored subjects, such as areas planted with upland rice, have the potential to achieve not only higher yields, but also high rates of return. Our empirical findings are also relevant to the ongoing debate on the impact of climate change on food security. Crop productivity in less-favored lands, such as rice production in upland Brazil, is significantly correlated with changes in climate variability and global warming. Less-favored lands will bear the brunt of the adverse consequences from climate change. Improving food security and reducing poverty in these areas, where the capacity to adapt to global change is also weakest, still remains a challenge.

APPENDIX A: GENERALIZED ENTROPY INDEX OF SPATIAL YIELD VARIABILITY[12]

The Generalized Entropy (GE) measure (Shorrocks, 1980 and 1984) can be written as:

$$\mathrm{I(y)} = \begin{cases} \sum_{i=1}^{K} f(y_i)\left\{\left(\frac{y_i}{\mu}\right)^c - 1\right\} & c \neq 0,1 \\ \sum_{i=1}^{K} f(y_i)\left(\frac{y_i}{\mu}\right)\log\left(\frac{y_i}{\mu}\right) & c = 1 \\ \sum_{i=1}^{K} f(y_i)\log\left(\frac{\mu}{y_i}\right) & c = 0 \end{cases} \tag{1}$$

where y_i is yield in the i^{th} region, μ is the total sample mean, $f(y_i)$ is the area share of the i^{th} region in the total planting area, and K is the number of regions. Here, the region is either a county in China or a municipality in Brazil.

The valuable feature of the GE measure is that it is additively decomposable. For rice production systems indexed by *g*, the overall GE measure can be expressed as:

$$I(y) = \sum_{g}^{K} w_g I_g + I(\mu_1 e_1, \ldots, \mu_K e_K) \tag{2}$$

$$\text{where } w_g = \begin{cases} f_g\left(\frac{\mu_g}{\mu}\right)^c & c \neq 0,1 \\ f_g\left(\frac{\mu_g}{\mu}\right) & c = 1 \\ f_g & c = 0 \end{cases}$$

where I_g is inequality in the g^{th} rice production system (e.g. irrigated rice), μ_g is the mean of the g^{th} rice production system, and e_g is a vector of 1's of length n_g, where n_g is the planting area of the g^{th} rice production system. If *n* is the total planting area of a country, then $f_g = \frac{n_g}{n}$ represents the area share of the g^{th} production system in the country. The first term on the right side of (2) represents the within-group inequality, while $\frac{w_g I_g}{I(y)} * 100$ is the g^{th} group's contribution to total inequality. The second term is the between-group (or inter-group) component of total inequality.

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[12] This section is largely taken from Wood, You and Zhang (2004).

Following Zhang and Kanbur (2001), we define the polarization index, P, as:

$$P = \text{between-group inequality/total inequality} \quad (3).$$

The parameter c in the GE index represents the weight given to distances between regions or between production systems. For simplicity, we present results in this paper only for $c=0$.

APPENDIX B: RICE PRODUCTION SYSTEMS IN CHINA AND BRAZIL

Figure B.1. Rice production systems in China

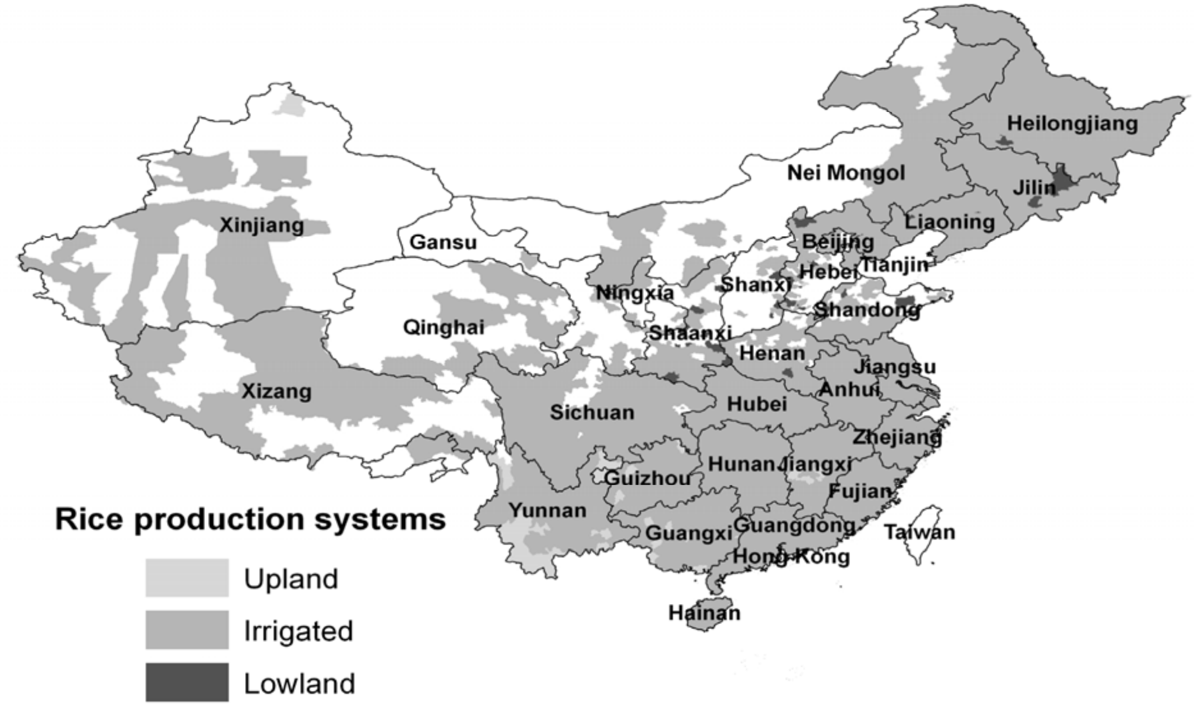
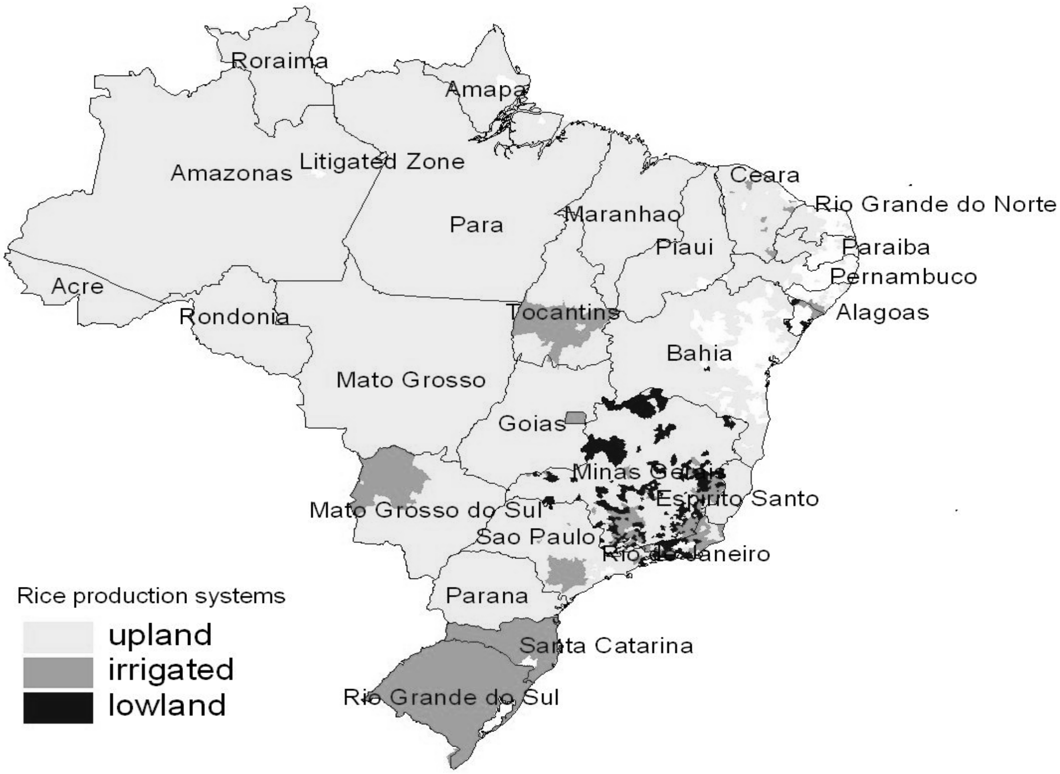


Figure B.2. Rice production systems in Brazil



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