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ECONOMIES OF SCALE AND SCOPE AND THE ECONOMIC EFFICIENCY OF CHINA'S AGRICULTURAL RESEARCH SYSTEM*

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This article investigates economies of scale and scope and other potential sources of improvements in the economic efficiency of China's crop breeding, an industry at the heart of the nation's food economy. Using data covering 46 wheat- and maize-breeding institutes from 1981 to 2000, we estimate cost functions for the production of new varieties at China's wheat- and maize-breeding institutes. Our results indicate strong economies of scale, along with small to moderate economies of scope related to the joint production of new wheat and maize varieties. Cost efficiency increases significantly with increases in the breeders' educational status and with increases in access to genetic materials from outside the institute.

1. INTRODUCTION

Crop-breeding centers in agricultural research institutes around the world played a major role in feeding the world's population during the 20th century (Borlaug, 2000). In the immediate aftermath of World War II and through the 1960s, scientists and politicians forecast serious food shortages and starvation across large parts of the world. Between 1960 and 2000, the world's population doubled, but over the same period, grain production more than doubled, an increase almost entirely attributable to unprecedented increases in yields. The Malthusian nightmare never materialized, mainly because scientific innovations produced new technological packages that raised productivity and expanded output beyond anyone's expectations (Pingali et al., 1997). New crop varieties made up the heart of these packages, although they were supplemented by improved water control, greater use of chemical fertilizers, and increased know-how.

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Despite the enormous successes in the second half of the 20th century, science has not eliminated the possibility of serious global food shortages, and agricultural research establishments must meet even greater challenges in the 21st century (Byerlee et al., 2000). Growth rates of yields slowed during the 1980s and 1990s and the yield gap—the difference between yields on experimental plots and farmers' fields—has shrunk (Pingali et al., 1997). When the slower growth rate of yield is coupled with rising demographic pressures and water and environmental concerns, new varieties that produce more food under increasingly challenging environments will be essential to meeting world demand, which is predicted to rise by 40% between now and 2025 (Rosegrant et al., 1999).

The task of those responsible for breeding new varieties, however, will have to be executed at a time when support for agricultural research in both developed and developing countries is waning. During the 1950s, 1960s, and 1970s, agricultural scientists enjoyed rapidly expanding budgets, but during the past two decades the growth has slowed. Pardey and Beintema (2001) reported a real growth rate of global agricultural research spending during 1976–81 of 4.5% per annum (7% in developing countries and 2.5% in developed countries), but by 1991–96 this growth rate had fallen to 2.0% per annum (3.6% in developing countries and 0.2% in developed countries). It has continued to decline since then. China is no exception. China's real annual growth rate of agricultural research expenditure fell from 7.8% in 1976–81 and 8.9% in 1981–86 to 5.5% in 1991–96 (Pardey and Beintema, 2001). Similar patterns but in more exaggerated terms can be seen in the expenditures of research institutes in developed or developing countries, and in the international agricultural research system, which includes centers (such as the International Rice Research Institute—IRRI) that are dedicated to crop varietal improvement (Pardey and Beintema, 2001). Hence, in an era of slower growth in agricultural research expenditures and increased demands for output, there will be rising pressure on the research system to come up with ways to produce more for less. In the parlance of production economics, this means that it will be necessary to become increasingly efficient at producing new varieties.

Although several authors have recognized the importance of economies of scale and economies of scope in agricultural research (Evenson, 1978; Ruttan, 1978; Pardey et al., 1991; Alston et al., 1995), few studies have attempted to measure the nature of the processes used by the agricultural research "industry" to create new varieties—the technology used to produce varietal technology, sometimes called the research production function. Since the seminal work of Baumol et al. (1982), economies of scale and economies of scope have been studied in a wide range of industries (e.g., Cowing and Holtmann, 1983; Murray and White, 1983; Gyimah-Brempong, 1987; Deller et al., 1988; Cohn et al., 1989; de Groot et al., 1991; Fournier and Mitchell, 1992; Wholey et al., 1996; Paul, 1999). However, only two studies—Branson and Foster (1987) and Byerlee and Traxler (2001)—have produced empirical evidence on economies of size in agricultural research, and there have not been any empirical studies on economies of scope. Moreover, the limited evidence on economies of size in agricultural research is mixed.

Based on a unique set of data, collected specifically to examine the production economics of crop-breeding centers, we use a cost function approach to estimate economies of scale, economies of scope, and other aspects of the technology of crop varietal production in China.[2] Although we are interested in the production economics of crop breeding in general, our focus on China is appropriate for several reasons. First, China has a long and successful history of crop breeding and, although it is a developing country, its breeders have made breakthroughs that rival those of most developed countries (Stone, 1988). Hence, in some sense, our findings are relevant for the breeding programs of all nations. In addition, China is important in its own right as the largest country in the world, and as an example of a large developing country. Many have predicted that such nations must bear much of the responsibility for producing the varieties that will feed the world in the coming decades (Huang et al., 2002). The large number of breeding centers in China, the decentralized nature of its research system, and the great heterogeneity among its centers offer a unique research opportunity to identify the relationship between varietal production, the size of institute, and mix of crops in the breeding program. Finally, the results are of interest to China's leaders, who recently have announced a new round of research reforms in agriculture (Huang et al., 2001).

To make our analysis tractable, and because of budgetary constraints, we limited the scope of our study to the breeding institutes of two crops (wheat and maize) within northern China. We chose crop-breeding institutes because crop breeding has been central to the growth of agricultural productivity in China (Huang and Rozelle, 1996; Jin et al., 2002) as well as in the world. In China, crop breeding takes the largest proportion of resources in its agricultural research system (Huang et al., 2001). Crop-breeding institutes were chosen also because their research outputs and their consequences can be measured relatively easily—compared with, say, less applied research, research oriented toward natural resources management, or research leading to disembodied technological change. Wheat and maize are two of the most important staple crops in China, ranking second and third, respectively, after rice in terms of sown area and production. Wheat and maize production occupy somewhat overlapping areas and a large share of China's wheat- and maize-breeding programs are located in the same institutes and similar regions, which allows us to measure economies of scope.[3]

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[2] A cost function (or dual) approach is preferred to a production function (or primal) approach because it allows us to directly test and measure both economies of scale and economies of scope between wheat- and maize-breeding programs. In addition, cost functions avoid the well-known econometric problems associated with endogenous right-hand-side variables, because they involve the prices rather than quantities of inputs, and prices are more likely to be exogeneous. On the other hand, cost functions involve stronger behavioral assumptions and their own econometric problems, as discussed in the text. To examine the robustness of the results, we also estimated production functions for new varieties, and we found strong evidence of economies of scale, consistent with those from the cost functions. (Results of the primal estimation can be found in the working paper version of this article, Jin et al., 2003, which is available at http://www.agecon.ucdavis.edu/ARELibrary/WP/03-003.pdf.)

[3] A natural extension to the study, if funds were available, would be to include rice, which is economically important and agronomically more similar to wheat in several senses and might therefore be expected to have research synergies with wheat. Wheat and rice, however, are grown primarily in different regions and it seems unlikely that great economies of scope could be realized by combining a rice institute in the south with a wheat institute in the north, let alone with maize.

We find striking evidence of strong economies of scale in crop breeding in China. The small and highly statistically significant coefficients of economies of scale imply a significant cost saving associated with expanding the scale of breeding institutes. Such results are robust to the specification of the output of the breeding process, whether we examine the production of wheat, maize, or both crops, and when we use an Instrumental Variables (IVs) approach to treat the errors-in-variables problem in our measure of actual output of varieties (a proxy for expected output of varieties). A number of other potential areas for gains in efficiency are identified, including the existence of some, though less strong, economies of scope between wheat and maize variety production. In short, there appears to be room to realize efficiencies by reorganizing crop research in China. Unfortunately, it is more difficult to identify the optimal size of breeding centers since we actually observe few institutions at or beyond the bottom of the long-run cost curve.

The rest of the article is organized as follows. In the next two sections, we discuss the data and present a set of descriptive results to illustrate the observed relationship between research output and costs. The following sections develop the empirical model and present the results of econometric analysis. Finally, we discuss the findings, analyze the implications of various reorganization schemes for cost savings, and conclude.

2. DATA

Most of the data used in this study were collected by the authors during 12 months of field work in China that began in the summer of 2001. Enumerators assembled panel data from 46 wheat- and maize-breeding institutes covering the years from 1981 to 2000. The sample institutes include 40 prefectural-level institutes and 6 provincial-run institutes, selected at random from a comprehensive list of prefectural and provincial institutes in seven major wheat and maize provinces in northern China.[4] Thirty-two of the sample institutes produce both wheat varieties and maize varieties (in short, *joint wheat and maize* institutes). Four institutes specialize in producing wheat varieties (*wheat-only* institutes). The other 10 produce only maize varieties (*maize-only* institutes).[5]

To collect the data, teams of enumerators visited each institute for periods of up to 1 week and completed a set of questionnaires filled out by accountants and by enumerators. In general, the data cover four broad categories: income, costs, research output, and data on other characteristics of the institute. Since the data were not kept by a single department in any of the institutes, a great deal of cross-checking was needed to make the data consistent among the various departments.

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[4] The total wheat sown area and total maize sown area in these seven provinces in 2000 were, respectively, 16,900,000 and 14,500,000 hectares, accounting for 57% and 62% of the national total. The total sown area of wheat (or maize) planted with the varieties produced from the 46 institutes reached 9,340,000 (or 8,530,000) hectares, accounting for more than 55% (or 60%) of the total sown area in these provinces.

[5] We use "wheat" institute (or "maize" institute) to refer to any institute that produces wheat (maize) varieties, even if it is jointly with varieties of another crop.

For example, the research coordination department typically kept information on income and expenditures. Personnel departments provided the data on salaries, educational accomplishments, and other information about current and past staff. Breeders kept the best information on the varieties they produced and the methods that they used in their breeding efforts.

To examine cost efficiency, information is needed on two key variables, costs and output, especially since there is an a priori reason to believe that the small scale of many institutes may be an important source of inefficiency. In using our survey data to define measures of these key variables, we have had to deal with several methodological issues. As an economic activity, crop breeding has several characteristics that make it relatively hard to measure output and match measures of output to measures of costs associated with those outputs. These characteristics include the long lags between the time when costs are incurred and the resulting output is realized (and hence an inability to observe actual output when expenditure decisions are being made), uncertainty about what is an appropriate measure of output both conceptually and in practice (given that varieties are not sold on a market and vary considerably in quality), and the fact that output itself is uncertain when costs are incurred (only a few varieties are released and become commercially successful in a given year, and for some institutions in a given year the number is 0).[6]

Our measure of the total variable costs of each crop's breeding activities includes the institute's operating expenses, such as salaries, project administration, and other direct operating expenses. For cost categories that cannot be matched directly to a breeding project (for example, transportation costs, administration, or costs associated with certification), we assigned a share of the costs of each category to breeding according to the number of full-time breeding staff (that is, the ratio of the number of full-time breeding staff to the total number of employees in the institute). We deflated total variable costs by a provincial consumer price index, putting our cost figures into real 1985 terms (SSB, 1981–2001).

We assume that the products of China's wheat and maize variety "factories" are the varieties that the breeders produce that are adopted by farmers. To measure output, we collected information on (i) the number of varieties that were produced by the research institutes (conditional on their being adopted by farmers), (ii) the area sown to the varieties, and (iii) the trial yields of each variety (which is the yield that is part of the certification record of the variety during the year that it is released). With these data, we constructed four measures of research output: (i) the *number of varieties* released by the institute sown in the field during a given year, (ii) the number of varieties, weighted by the trial yields of the variety

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[6] These are quite general conceptual and measurement problems in empirical production economics, but they are more pronounced in applications to crop breeding than in many other production processes given the small (integer) output, measured as varietal releases, the cumulative nature of the development of "knowledge," and the lags of many years between investments in research and the production of a variety. In other settings, too, it is often difficult to translate information about continuous, long-time, dynamic processes meaningfully into discrete, matching, observations of costs and output that can be used in a static model of the technology of production. But in practice it is common simply to ignore the issues.

(in short, *yield-weighted output*), (iii) the total area sown to all of the institute's varieties during a given year (*area-weighed output*), and (iv) the number of varieties weighted by sown area and trial yields (*yield-area weighted output*).[7]

Each of the four output measures has strengths and weaknesses. Although it is the most readily measured, the obvious flaw with the number of varieties is that it does not take into account any quality characteristics of each variety, either yield or its other characteristics (such as its level of insect resistance or other qualities that could make it attractive to farmers). Yield-weighted output accounts for the relative productivity of a variety in pure output terms. However, such a measure still leaves out all other quality characteristics, which an earlier study shows may be highly valued by farmers (Jin et al., 2002). For this reason, our third measure, area-weighted output, should be superior to the other two measures. If farmers value the characteristics in a variety—whether high yields or some other characteristic—they demonstrate their preference by adopting the variety (Byerlee and Traxler, 2001). The last measure, yield-area weighted output combines the second and third measures. Since the variation in trial yields is small, the correlations between the third and fourth output measures are high (0.99 for wheat; 0.95 for maize). Hence, we would not expect much difference to result from using one versus the other.

One special feature of crop variety production is the significant time lag between the time when costs are incurred in a breeding research program and the time when the resulting research output (if any) is realized. This issue is commonly discussed in studies of the returns to agricultural R&D (Alston et al., 2000; Fan, 2000), especially in relation to specification of econometric models relating agricultural productivity to research expenditures. In the present setting, the lag between investment and output has some further (and different) implications, akin to those that arise more generally in agricultural production economics, associated with biological lags. In microeconomic theory texts, the firm manager first chooses an output level (or combination of output levels), and then determines the combination of inputs that will produce that output at minimum cost. The crop-breeding institute's director does not have that luxury, because the output from today's investment is uncertain and will not be known for many years (this uncertainty applies both to the quality and quantity of the research output and to when it will be obtained and over what period the benefits will flow).

As an approximation to this problem of decision making under uncertainty, we might suppose that the director seeks to minimize the institute's cost based on current expectations of the output that will be produced in the future as a result of the current research expenditures. Unfortunately, we cannot observe or measure, ex post, such expectations. One option is to use the output that was

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[7] The *yield-weighted output* of each research institute is constructed as follows. First, we divide the trial yield of each variety by the grand mean trial yield of all the varieties for all the years of the same crop (either wheat or maize). This gives us an index number for each variety. The index numbers for wheat, for example, range between 0.61 and 1.46. The index number is less than 1 if the variety has a trial yield that is less than grand mean of the trial yields and greater than 1 if the variety has a trial yield that is greater. In the second step, we create the institute-specific measure, yield-weighted output, for each year by summing the index numbers of all the institute's varieties that are being used in the field by producers in that year.

actually produced from the expenditures as a proxy of those expectations, but the problem remains of matching actual outputs to particular expenditures (an example of what Alston and Pardey, 2001, termed the "attribution problem" in agricultural research evaluation).

To deal with this problem empirically, we defined an average research lag to represent the number of years between the time when a breeding project officially begins (in China, this is usually when a formal research project is granted by a funding agency to the institute) and the time when a variety is released for commercial extension to the fields of farmers. Using this defined lag length, we modeled the cost of variety production as a function of the research output produced after a certain lag. To find the length of lag, we designed a section of the questionnaire to ask breeders in each of the 46 institutes specifically to estimate the average lag length for each crop. Based on the data we collected, the average lag length was 5.3 years for wheat and 4.5 years for maize. In our base model, we used a 5-year lag for both wheat and maize variety production. However, we also tried different lag lengths to check the robustness of our results.

3. THE PRODUCTION OF VARIETIES AND THE COST OF BREEDING

China's agricultural research system has produced a steady flow of crop varieties in the past. On average, in each year during the period 1982–95, China's farmers grew 200–300 wheat varieties and 130–180 maize varieties in their fields (Jin et al., 2002). However, the number of new varieties being produced by research institutes varied significantly over time and across institutes. Based on our survey, 141 wheat varieties and 155 maize varieties were produced by our sample institutes during the period 1985–2000 (Table 1). Nineteen percent (26%) of the wheat (maize) varieties were developed by provincial institutes. The rate of production of new wheat and maize varieties increased over time. For example, prefectural maize institutes produced 34 maize varieties during 1985–90, 47 varieties during 1990–95, and 74 during 1995–2000. The number of wheat varieties created and commercialized by the sample institutes rose from 31 in 1985–90 to 55 during each subsequent period (1990–95 and 1995–2000).

The number of varieties, however, varies sharply among institutes. For example, the Henan provincial wheat institute produced 12 wheat varieties from 1985 to 2000. The Mianyang prefectural crop-breeding institute in Sichuan produced 14 wheat varieties. In contrast, 24 (or 67%) out of 36 of the sample wheat institutes produced fewer than five varieties. In fact, three wheat institutes did not produce a single variety during the entire 15-year sample period. Maize variety production also varies greatly among the sample institutes.[8]

3.1. *Variety Production Costs and Scale.*

In the same way that output varies across time and space, so does total cost. On average, the annual total variable

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[8] For example, the Shandong provincial maize institute and the Dandong prefectural institute in Liaoning provinces produced 12 and 19 maize varieties for the same time period, whereas the majority of the institutes, 29 (or 69%) of the 42 maize institutes produced fewer than five varieties. Five (or 12%) of the 42 maize institutes produced zero varieties during the 15 years.

TABLE 1

NUMBER OF VARIETIES RELEASED AND AREA OF ADOPTION FOR DIFFERENT TYPES OF INSTITUTES, 1985–2000

	No. of Varieties Released				Area Adopted of Released Varieties (1000 ha)			
Institute Type	1985–90	1991–95	1996–2000	All	1985–90	1991–95	1996–2000	All
				Wheat Institutes				
Provincial institutes	6	11	10	27	769	9391	7499	17,658
	(19)[a]	(20)	(18)	(19)	(9)	(30)	(17)	(21)
Prefectural institutes	25	44	45	114	7980	22,170	36,195	66,345
	(81)	(80)	(82)	(81)	(91)	(70)	(83)	(79)
All institutes	31	55	55	141	8749	31,561	43,694	84,004
				Maize Institutes				
Provincial institutes	8	15	17	40	1858	5835	17,128	24,821
	(24)	(32)	(23)	(26)	(21)	(36)	(46)	(40)
Prefectural institutes	26	32	57	115	7099	10,387	19,814	37,300
	(76)	(68)	(77)	(74)	(79)	(64)	(54)	(60)
All institutes	34	47	74	155	8957	16,222	36,942	62,121

[a] Numbers in parentheses are percentages of column subtotals (e.g., six wheat varieties released by prefectural institutes during 1985–90. The six varieties account for 19% of total number of varieties released during that period).

costs of the breeding program per institute for our sample of wheat institutes, measured in real 1985 terms, increased from 24,000 yuan to 38,000 yuan between 1981 and 2000. Similarly, the average annual real total variable breeding cost for our sample of maize institutes rose from 38,000 to 53,000 yuan.[9] The total cost of wheat and maize breeding, however, varies greatly among institutes. For example, the average provincial institute invested five times more in wheat breeding and about six times more in maize breeding than the average prefectural institute did. When comparing prefectural breeding stations, the total cost of wheat breeding in one institute (e.g., the Yantai prefectural institute of Shandong Province or the Mianyang prefectural institute in Sichuan Province) could be more than three times that of the average prefectural institute. Dandong prefectural institute in Liaoning spent five times more than the average maize-breeding institute did.

The average cost of variety production (measured in cost per unit of output) also varies from institute to institute and can be seen to vary systematically with research output. To compare costs and output, we have to account for the research lag. In the analysis that follows, research output is the annual mean of 5 years' total research output from one of three 5-year periods, 1985–90, 1991–95, and 1996–2000. The average annual cost associated with this output is the annual mean of 5 years' total cost, lagged by 5 years. Therefore, the corresponding three 5-year periods of cost are, respectively, 1980–85, 1986–90, and 1990–95.

Unlike total costs, average costs fall as the institutes produce more varieties (Table 2). For wheat (maize) the cost per variety falls from 152,000 yuan (150,000 yuan) for breeding institutes that produce only one variety to 60,000 yuan

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[9] In year 2000 purchasing power parity terms, the annual total variable cost of a wheat institute (or maize institute) increased from US $44,000 (or US $71,000) to US $71,000 (or US $99,000).

TABLE 2

NUMBER OF VARIETIES, TOTAL COST, AND AVERAGE COST FOR WHEAT- AND MAIZE-BREEDING INSTITUTES BASED ON THREE 5-YEAR PERIODS

Research Output Based on Number of Varieties

Wheat Program			Maize Program		
Research Output (No. of Varieties)	Total Cost (1000 Yuan in Real 1985 Terms)	Average Cost per Variety (1000 Yuan in Real 1985 Terms)	Research Output (No. of Varieties)	Total Cost (1000 Yuan in Real 1985 Terms)	Average Cost per Variety (1000 Yuan in Real 1985 Terms)
0	66.41	n.a	0	92.31	n.a
1	152.42	152.42	1	146.96	146.96
2	172.43	86.22	2	161.67	80.84
3	204.76	68.25	3	242.07	80.70
>4	276.25	60.56	>4	485.41	66.07

Research Output Based on Sown Area

Wheat Program			Maize Program		
Research Output (1000 ha)[a]	Total Cost (1000 Yuan in Real 1985 Terms)	Average Cost per Hectare of Sown Area (1985 Real Yuan)	Research Output (1000 ha)[a]	Total Cost (1000 Yuan in Real 1985 Terms)	Average Cost per Hectare of Sown Area (1985 Real Yuan)
0.00	63.9	n.a.	0.00	73.7	n.a.
10.58	94.6	16.0	3.64	81.7	37.5
64.02	98.3	1.9	27.17	115.2	4.9
288.11	133.5	0.6	160.03	167.0	1.3
3134.69	319.0	0.1	1506.26	308.0	0.3

[a] Approximately 20% of observations in each category.

(66,000 yuan) for those that produce more than four varieties. Similar patterns can be seen in the data when using area-weighted output. A plot of the data reveals a distinct L-shaped relationship between average cost and the size of research output (Figure 1).[10] No matter what measure of output is used, or for what crop, as research output increases, the average cost of breeding research falls. The L-shaped relationship also is robust, holding over time and over institutes. The sharp fall in average costs of breeding as an institute's output rises suggests that China's wheat and maize research institutes are producing in an output range with strong economies of scale, such that efficiency might be increased by expanding the scale of production of China's wheat and maize research institutes.

3.2. *Economies of Scope and Other Determinants of Breeding Costs.* The data also show some evidence that average costs fall with increases in output in joint

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[10] For each data point on the graph, research output is the annual mean of 5 years' total research output from one of the three 5-year periods (i.e., 1985–90, 1991–95, and 1996–2000), for which costs were incurred in the corresponding three 5-year periods, 1980–85, 1986–90, and 1991–95, respectively.

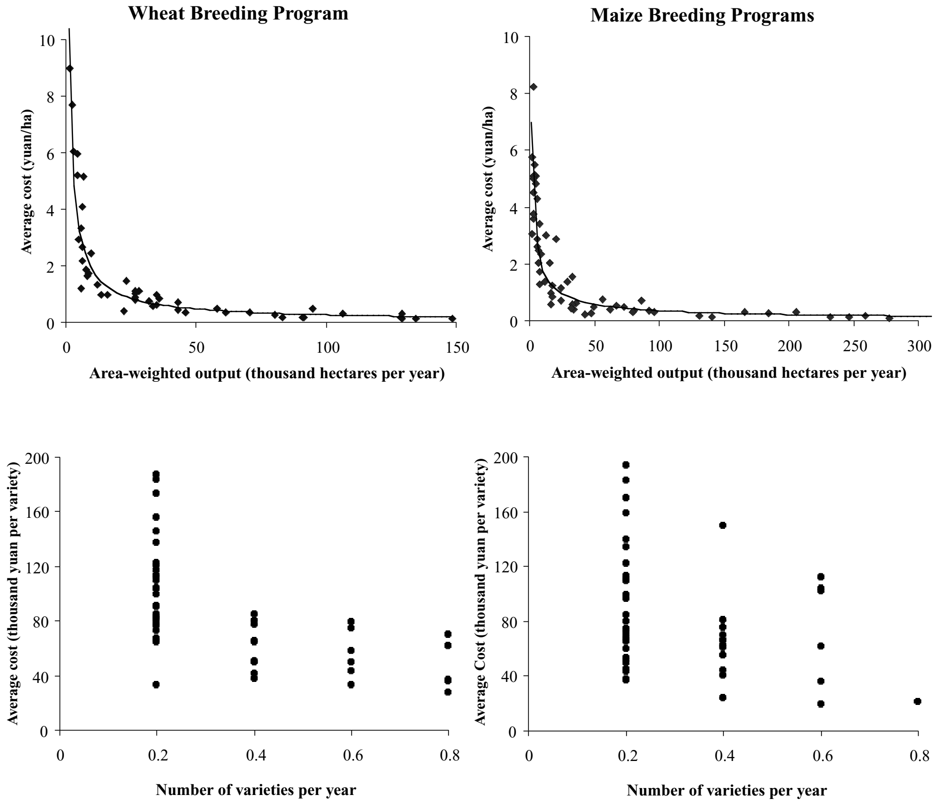

FIGURE 1

AVERAGE COST OF WHEAT-AND MAIZE-BREEDING RESEARCH AND RESEARCH OUTPUT

wheat and maize institutes. The average cost per wheat variety is consistently lower in joint (wheat and maize) institutes than in wheat-only institutes. Similarly, the average cost per maize variety is consistently lower in joint institutes compared with maize-only institutes. For wheat (or maize), the cost per variety falls from 187,000 yuan (225,000 yuan) in wheat-only institutes (maize-only institutes) to 145,600 yuan (128,900 yuan) in joint wheat and maize institutes. The same patterns also appear in the data when the area-weighted output measure is used instead of the number of varieties. Moreover, the evidence of economies of scope becomes stronger as the scale of research effort increases. Hence, our descriptive data provide evidence that economies of scope may be a source of efficiency differences among institutes. The evidence of economies of scope suggests a potential cost saving associated with combining a wheat-only institute and a maize-only institute into a bigger, joint, wheat and maize institute.

Further analysis of the data also points to other factors that potentially could affect costs, although in some cases the descriptive statistics do not show a particularly strong correlation. The relatively low education level of China's agricultural researchers has long been claimed to be one of the key factors limiting agricultural

TABLE 3

AVERAGE COST OF WHEAT (OR MAIZE) VARIETY PRODUCTION AND INSTITUTIONAL CHARACTERISTICS

Rank by Average Cost (Lowest to Highest 20 Percentile)	Share of Breeders with College and above Education	Share of Scientists Working on Other Disciplines	Share of Genetic Materials from Outside Provinces	Share of Retirees[a]
		Wheat Institutes		
1	0.56	0.43	0.29	0.19
2	0.47	0.51	0.25	0.31
3	0.41	0.47	0.28	0.16
4	0.41	0.51	0.18	0.30
5	0.44	0.51	0.31	0.23
Average	0.46	0.48	0.26	0.24
		Maize Institutes		
1	0.48	0.48	0.15	0.21
2	0.44	0.44	0.17	0.28
3	0.47	0.53	0.19	0.25
4	0.36	0.48	0.29	0.22
5	0.42	0.44	0.17	0.20
Average	0.43	0.47	0.19	0.23

[a] Share of retirees is measured as the ratio of total salary payments of the retirees in the institute to the total salary payments of the entire institute.

research productivity (Huang et al., 2001). Based on our data, the human capital in China's wheat- and maize-breeding institutes is low compared with other countries (46% of wheat breeders and 43% of maize breeders with "BS degree and above" education in China's wheat and maize institutes, compared to 80% of research staff with "BS and above" education in Latin America; Echeverria, 1998). Our data also show that increases in the educational level of breeders help to reduce the cost of variety production. The institutes that have the highest average cost of variety production (both wheat and maize varieties) also tend to have the lowest proportion of breeders with postsecondary education (Table 3). Byerlee and Traxler (2001) suggest that efficiency in crop breeding increases when agricultural scientists from other disciplines (e.g., agronomy and plant pathology) work in conjunction with breeders. Although the share of scientists working on other agricultural disciplines in wheat- and maize-breeding institutes is quite high (48% or 47%—Table 3), compared to 30% in an average wheat improvement research program in a developing country (Bohn et al., 1999), there is little difference in this share between institutes with low and high average costs. Finally, it is also unclear from visual inspection of the data in Table 3 whether breeding efficiency is affected by the source of a breeding institute's genetic materials (i.e., either from outside or from within the province) or the presence of retirees.

4. EMPIRICAL MODEL

In this section, we specify the econometric model to be used to study the efficiency of China's crop-breeding institutes and discuss our strategy for estimating the model. We begin by specifying the relationship between costs and the factors that affect them in institutes that produce either one or two types of varieties (maize or wheat). We also define measures for economies of scale, ray economies of scale, and economies of scope.

Here, we treat a breeding institute as a typical "firm," which applies inputs (in this case scientist time and other research inputs) to produce research output (new varieties). The total variable cost of an individual institute is expressed as a function of its research output, the price of its inputs, and other institutional characteristics affecting the cost structure of crop-breeding research.[11] A wide range of different types of cost functions (e.g., Cobb–Douglas, Generalized Quadratic, Translog, or Generalized Leontief) have been applied in the literature. We chose a flexible quadratic cost function, which we can express in a single-output setting as

$$\begin{aligned} C_{it}^{j} &= \alpha_0^{j} + \alpha_y^{j}\bar{Y}_{it}^{j} + \alpha_{yy}^{j}\left(\bar{Y}_{it}^{j}\right)^2 + \alpha_w^{j}W_{it}^{j} + \alpha_{ww}^{j}\left(W_{it}^{j}\right)^2 + \alpha_{yw}^{j}\bar{Y}_{it}^{j}W_{it}^{j} + \sum_{k=1}^{4}\beta_{z_k}^{j}(Z_k)_{it}^{j} \\ &\quad + \sum_{k=1}^{4}\beta_{yz_k}^{j}\bar{Y}_{it}^{j}(Z_k)_{it}^{j} + \sum_{t=1}^{T-1}\delta_t Time_t + \sum_{m=1}^{m-1}\varphi_m Province_m + \sum_{n=1}^{N-1}\phi_n Crop_n + \varepsilon_{it}^{j} \end{aligned} \tag{1}$$

where C_{it}^{j} is the total variable cost of breeding research for crop j ($j =$ wheat or maize) in institute i during the 5-year time period ending in year t; $\bar{Y}_{it}^{j} = (\sum_{l=5}^{9} Y_{i,t+l}^{j})/5$ is the yearly average of the research outputs that are produced during the 5-year period immediately after the 5-year period in which the cost is incurred; W_{it}^{j} is the annual wage rate of scientists; and Z_k is the kth of four institutional characteristics: a *human capital* variable (the share of breeders with BS degree or higher education), *other scientists* (measures of the proportion of nonbreeders in the agricultural scientific staff), *a spill-in variable* (the proportion of genetic material from outside), and *a retiree effect* (the number of retirees supported by the institute as a proportion of total staff). We also included dummy variables to capture the effects of time, province, and the type of institute (i.e., wheat-only, maize-only, and joint wheat and maize institutes). The terms α, β, δ, and ϕ and φ are parameters to be estimated.

Since most institutes produce both wheat and maize varieties, we also specify a multiple-output cost function:

$$\begin{aligned} C_{it} &= \alpha_0 + \sum_{j=1}^{2}\alpha_y^{j}\bar{Y}_{it}^{j} + \sum_{j=1}^{2}\sum_{r=1}^{2}\alpha_{yy}^{js}\bar{Y}_{it}^{j}\bar{Y}_{it}^{r} + \alpha_w W_{it} + \alpha_{ww}(W_{it})^2 + \sum_{j=1}^{2}\alpha_{yw}^{j}\bar{Y}_{it}^{j}W_{it} \\ &\quad + \sum_{k=1}^{4}\beta_k(Z_k)_{it} + \sum_{j=1}^{2}\sum_{k=1}^{4}\beta_{yz_k}^{j}\bar{Y}_{it}^{j}(Z_k)_{it}^{j} + \sum_{t=1}^{T-1}\delta_t Time_t + \sum_{m=1}^{M-1}\varphi_m Prov_m \\ &\quad + \sum_{n=1}^{N-1}\phi_n Crop_n + \varepsilon_{it} \end{aligned} \tag{2}$$

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[11] The important behavioral assumption in this model is that research institutes make prior choices of input in order to minimize the total variable cost to achieve a prior choice of certain level of research output. Since the actual level of output is not achieved until several years have passed, research institute managers are assumed to be minimizing costs of expected output.

where all of the variables and the parameters are defined the same way as in Equation (1). The only difference between Equations (1) and (2) is that the total variable cost of Equation (2) is now the sum of total variable costs of the wheat program and the maize program of each institute, and there is an interaction term (between the two outputs) on the right-hand side. This term will be used to measure the effect of the interaction between wheat and maize variety output on total variable cost.

4.1. *Economies of Scale, Ray Economies of Scale, and Economies of Scope.* To assess the effects of some of the plans that have been discussed by agricultural research reformers—to merge, consolidate, or reconstitute China's existing research institutes—we need to understand the efficiency that can be realized if the scale or scope of research institutes is broadened. Following Christensen and Greene (1976) and others, the coefficient of economies of scale (SCE) is simply the cost-output elasticity:

$$SCE = \partial \ln C / \partial \ln Y \tag{3}$$

where $SCE < 1$ indicates the presence of economies of scale and $SCE > 1$ indicates diseconomies of scale. In the context of our study, economies of scale of variety production of a crop-breeding institute means that the total cost of running a breeding program rises less than proportionately as output (e.g., the number of varieties) expands. The coefficient of economies of scale of crop j's (wheat-only or maize-only) institutes can be calculated directly from Equation (1). After the data have been normalized at their mean, the cost elasticity with respect to research output (measure of economies of scale) of the model defined in (1) is $SCE = \alpha_y^j + 2\alpha_{yy}^j + \alpha_{yw}^j$.

The elasticity of cost with respect to output when using results from multiple-output cost functions is the measure of ray economies of scale, (SCE^{ray}) defined as the proportionate change in cost resulting from a proportionate change in all the outputs:

$$SCE^{ray} = \sum_{i=1}^{2} \partial \ln C / \partial \ln Y_i \tag{4}$$

This is the sum of elasticities of total cost with respect to two outputs, where C in (4) refers to a multiple-output cost function as defined in (2). We say there are ray economies of scale if $SCE^{ray} < 1$ and ray diseconomies of scale if $SCE^{ray} > 1$. The presence of ray economies of scale implies that if a wheat and maize institute increases the production scale of wheat varieties and maize varieties simultaneously in fixed proportions, the total cost of wheat and maize variety production will increase less than proportionately. The coefficient of ray economies defined in (4) can be calculated directly from the estimates of the multiple-output cost function defined in Equation (2). For example, the measure of ray economies of scale of the multiple-output cost function defined in (2) is $SCE^{ray} = \alpha_y^1 + \alpha_y^2 + 2\alpha_{yy}^{11} + 2\alpha_{yy}^{12} + 2\alpha_{yy}^{22} + \alpha_{yw}^1 + \alpha_{yw}^2$.

Economies of scope (SOE) refers to the economies associated with the composition of output. It is a concept that can be measured with the estimates of Equations (1) and (2), the two separate single-output cost functions and the multiple-output cost function. Following Baumol et al. (1982), we can measure the economies of scope between wheat and maize variety production by the following definition:

$$SOE^{1,2} = [C(Y_1, Y_2) - C(Y_1, 0) - C(0, Y_2)]/C(Y_1, Y_2)] \tag{5}$$

where $C(Y_1,Y_2)$ is the multiple-output cost function of joint production of wheat and maize varieties defined in (2); $C(Y_1,0)$ is a cost function when only wheat is produced and $C(0,Y_2)$ is a cost function when only maize is produced; Y_1 refers to wheat varieties and Y_2 refers to maize varieties. Economies of scope are said to exist if $SOE^{1,2} < 0$, and diseconomies of scope if $SOE^{1,2} > 0$. Intuitively, economies of scope between wheat and maize variety production implies that the cost of producing wheat and maize varieties jointly is less than the cost of producing them separately. There are several sources for the existence of economies of scope between wheat and maize variety production, such as the sharing of administration cost, support staff, experiment fields, and other facilities.

Empirically, $SOE^{1,2}$ can be calculated and evaluated at the mean of the sample based on the estimation of (1) and (2). To do this, we predict $C(Y_1,Y_2)$ based on the estimates of multiple-output cost function defined in (2) evaluated at the mean values of all the right-hand side variables. We can also predict $C(Y_1,0)$ and $C(0,Y_2)$ based on the estimates of single-output cost functions defined in (1) evaluated at the means of all the explanatory variables. We can then substitute the predicted values for $C(Y_1,Y_2)$, $C(Y_1,0)$, and $C(0,Y_2)$ into (5) to compute $SOE^{1,2}$ and evaluate the economies of scope in the production of wheat and maize varieties. Finally, we can obtain the confidence interval of the coefficient of $SOE^{1,2}$ by “bootstrapping.”

4.2. *Estimation Strategy.* We estimate economies of scale and scope in two ways: (i) from a base model, where we estimate the relationship between cost and output taking account of the effects of annual salaries (or prices), time, province, and institute type (this is Equation (1) without the Z variables); and (ii) from a *full model*, which also includes the four covariates (and their interaction terms with output). In the final section, we discuss the implications for economic efficiency of crop breeding that can be drawn from the estimated relationship between cost and output after controlling for other variables (Z). We do so for both Equation (1), the single-output cost function, and Equation (2), the multiple-output cost function. Hence, in our analysis, we have four fundamental components: the base model for the single-output cost function (one for wheat and one for maize), the full model for the single-output cost function (also one for wheat and one for maize), and the base and full models for the multiple-output cost function.

We estimate the base cost function model with ordinary least squares (OLS) to get initial estimates of economies of scale and scope. However, the OLS estimates of the parameters may be underestimated if there is measurement error in the construction of the output variable (Deaton, 2000). One source of measurement error arises from the special nature of crop breeding and the decision making of its directors. The implicit behavioral assumption that underlies the cost function is that the research manager minimizes costs given the output of the institute. Such an assumption, even for a quasi-productive entity like a research institute, often has been made in cost analyses (e.g., in studies of hospitals by Cowing and Holtmann, 1983, and by Fournier and Mitchell, 1992; in studies of universities by Cohn et al., 1989 and by de Groot et al., 1991). Although it is not difficult to imagine that the typical research manager in a breeding station strives to minimize the institute's costs of given output, one characteristic that makes the plant breeding industry special is the long time lag between expenditure and the realization of the output.

We are assuming that research managers make their cost-minimizing expenditure decisions based on the expected output of the breeding station. But the econometrician does not observe expected output; only actual output is measured. We measure actual output from a crop-breeding institute as the number of new varieties from that research institute adopted by farmers (or the area of them sown) in the 5-year period, 6–10 years after the research expenditure. This measure might vary systematically from the output that the manager was anticipating when expenditure decisions were made. One solution to measurement error is the use of IVs (Greene, 1997). In order to account for the measurement error, we identify a set of IVs and reestimate our model using three-stage iterative least squares. Since the relationship between output and cost basically depends on factors associated with supply-side decisions of the research institute, we turn to a series of demand-side factors in our search for exogenous IVs: farm-gate prices of wheat and maize, the prices of fertilizer and pesticides in input markets, the land–labor ratio in a region, the share of irrigated land to total cultivated land, and the multiple cropping index.

We are also concerned with several other assumptions. In order to test for the effect of our assumption about the length of the lag between costs and research output (according to our survey, the mean lag reported by breeders was 5 years, but the range was between 3 and 7 years), we conducted sensitivity analysis using data generated by an array of different lag structures. Further, the presence of unobserved heterogeneity may bias the estimates of our parameters of interest. To eliminate the unwanted covariance between the unobserved factors and the other regressors, we took advantage of the panel nature of the data, using both fixed- and random-effects methods. Finally, it is also possible that the cost minimization assumptions that underlie cost function analyses may not all be valid. As noted above, these assumptions are avoided—albeit, at the expense of some other disadvantages—when we use a production function approach instead of a cost function approach. As a check on this aspect, we also estimated a Cobb–Douglas production function model, and found that the main findings regarding returns to scale are quite similar between the two approaches.

5. ESTIMATION RESULTS

The base model produced remarkably robust estimates of many of the parameters (Tables 4–6). The quadratic specification fits the data well with R^2 estimates

TABLE 4

SINGLE-OUTPUT COST FUNCTION OF WHEAT (OR MAIZE) VARIETY PRODUCTION OF PREFECTURAL INSTITUTES WITH BASE SPECIFICATION

	Wheat-Breeding Program				Maize-Breeding Program			
	Area-Yield Weighted Output	Area-Weighted Output	Number of Varieties	Yield-Weighted Output	Area-Yield Weighted Output	Area-Weighted Output	Number of Varieties	Yield-Weighted Output
Output	−0.152***	−0.107***	−0.143	−0.085	−0.175***	−0.169**	0.175	0.215*
	(2.90)	(2.65)	(1.21)	(0.81)	(2.69)	(2.46)	(1.31)	(1.91)
Output squared	−0.006	−0.005	0.069***	0.021	−0.018***	−0.020***	0.027***	0.021***
	(1.34)	(1.56)	(4.51)	(1.32)	(6.28)	(6.54)	(3.48)	(3.72)
Salary	1.721***	1.297**	−0.380	0.050	0.486	0.480	−0.404	−0.286
	(3.20)	(2.54)	(0.59)	(0.09)	(0.91)	(0.89)	(0.57)	(0.51)
Salary squared	−0.776***	−0.552**	0.300	0.063	−0.117	−0.127	0.576*	0.475*
	(3.02)	(2.26)	(0.98)	(0.23)	(0.46)	(0.49)	(1.68)	(1.72)
Output × Salary	0.385***	0.336***	0.264**	0.292***	0.523***	0.532***	−0.070	−0.123
	(9.92)	(8.60)	(2.32)	(2.90)	(10.15)	(9.87)	(0.54)	(1.12)
Dummy of wheat institute	−0.437***	−0.403***	−0.366***	−0.328***				
	(5.33)	(5.16)	(3.68)	(3.89)				
Dummy of maize institute					0.344***	0.409***	0.671***	0.511***
					(2.65)	(3.14)	(3.99)	(3.90)
Constant	0.025	0.212	1.029***	0.617**	0.322	0.328	0.613	0.450
	(0.09)	(0.79)	(3.01)	(2.14)	(1.14)	(1.14)	(1.64)	(1.55)
Observations	352	352	352	352	399	399	399	399
R^2	0.72	0.75	0.60	0.53	0.72	0.71	0.52	0.53
Economies of scale	0.22***	0.22***	0.26***	0.25***	0.31***	0.32***	0.16***	0.14***
	(21.04)	(33.46)	(20.49)	(17.38)	(26.80)	(25.76)	(23.15)	(29.20)

Numbers in parentheses are the absolute values of t-statistics for the test of the null hypothesis that the coefficient is equal to 0 (versus not equal to 0) except for the last row, where numbers in parentheses are the absolute values of t-statistics for the test of the null hypothesis that the coefficient of economies of scale is equal to 1 (versus less than 1).

*Significant at 10%.

**Significant at 5%.

***Significant at 1%.

Time and regional dummies are included in the model, but we do not present the results in this table.

TABLE 5

SINGLE-OUTPUT COST FUNCTION OF WHEAT (OR MAIZE) VARIETY PRODUCTION WITH OTHER INSTITUTIONAL VARIABLES, BASED ON YIELD-AREA WEIGHTED OUTPUT

	Wheat-Breeding Program		Maize-Breeding Program	
	Human Capital + Spill-In Variable	Full Model	Human Capital + Spill-In Variable	Full Model
Output	0.257***	0.358***	0.078	−0.141
	(3.09)	(3.73)	(1.06)	(1.35)
Output squared	−0.009**	−0.013***	−0.023***	−0.025***
	(2.24)	(3.31)	(8.10)	(8.69)
Salary	1.382***	1.296**	0.310	0.257
	(2.69)	(2.54)	(0.62)	(0.52)
Salary squared	−0.595**	−0.596**	0.016	0.009
	(2.41)	(2.43)	(0.07)	(0.04)
Output × Salary	0.347***	0.293***	0.494***	0.587***
	(8.87)	(7.06)	(10.18)	(10.69)
Share of breeders with college education	0.102*	0.039	0.101**	0.164***
	(1.67)	(0.66)	(2.00)	(3.09)
Output × Share of breeders with college education	−0.089***	−0.001	−0.103***	−0.066**
	(4.31)	(0.05)	(3.81)	(1.99)
Share of genetic materials from outside	0.080	−0.012	0.067**	0.068**
	(1.42)	(0.39)	(2.22)	(2.21)
Output × Share of outside genetic materials	−0.225***	−0.236***	−0.134***	−0.129***
	(6.00)	(7.76)	(6.56)	(4.86)
Share of other scientists		0.057		−0.028
		(1.47)		(0.67)
Output × Share of other scientist		−0.103***		0.105***
		(3.22)		(2.97)
Share of retiree		−0.043		0.176***
		(1.00)		(4.14)
Out × Share of retiree		−0.017		−0.006
		(0.28)		(0.20)
Dummy of wheat institute	−0.465***	−0.363***		
	(5.88)	(4.58)		
Dummy of maize institute			0.127	0.073
			(0.96)	(0.55)
Constant	0.023	0.213	0.291	0.153
	(0.08)	(0.81)	(1.07)	(0.57)
Observations	352	352	399	399
R^2	0.75	0.77	0.76	0.77
Economies of scale	0.27***	0.27***	0.29***	0.30***
	(24.94)	(25.06)	(26.80)	(26.25)

Numbers in parentheses are the absolute values of t-statistics for the test of the null hypothesis that the coefficient is equal to 0 (versus not equal to 0) except for the last row, where numbers in parentheses are the absolute values of t-statistics for the test of the null hypothesis that the coefficient of economies of scale is equal to 1 (versus less than 1).

*Significant at 10%.

**Significant at 5%.

***Significant at 1%.

Time and regional dummies are included in the model, but we do not present the results in this table.

TABLE 6

COST FUNCTION OF WHEAT (OR MAIZE) VARIETY PRODUCTION WITH MEASUREMENT ERROR CORRECTED BY INSTRUMENTAL VARIABLES (OUTPUT MEASURE BASED ON YIELD-AREA WEIGHTED OUTPUT)

	Different Lag Length between Research Output and Cost		Panel Estimation		With Correction of Autocorrelation & Heteroskedasticity	Function Translog[a]
	7 Years	3 Years	Random Effect	Fixed Effect		
Economies of scale from single-output cost function of wheat programs	0.15*** (25.13)	0.23*** (28.32)	0.17*** (25.33)	0.14*** (19.73)	0.22*** (14.53)	0.15*** (8.64)
Economies of scale from single-output cost function of maize programs	0.33*** (21.56)	0.32*** (27.53)	0.19*** (36.08)	0.17*** (38.70)	0.22*** (23.11)	0.23*** (13.54)
Ray economies of scale from multiple-output cost function	0.30*** (20.17)	0.32*** (27.50)	0.22*** (28.77)	0.19*** (27.94)	0.28*** (18.52)	0.34*** (30.22)

All the economies of scale coefficients are calculated from base model specification; however, the results for all the different model specifications are consistent with the OLS results reported in Tables 5 and 6.

Numbers in the parentheses are the absolute values of *t*-statistics for the test of the null hypothesis that the coefficient of economies (or ray economies) of scale is equal to 1 (versus less than 1).

***Significant at 1%.

[a] In order to include those institutes with zero output in our regression, for the translog model we replaced zero values of outputs with a small number (0.0001), as suggested by Weninger (1998).

ranging from 0.53 to 0.75 for wheat and 0.52 to 0.72 for maize (Table 4). The goodness-of-fit measures, however, systematically demonstrate that, for both wheat and maize, the models that use the area-weighted and area-yield weighted outputs have a significantly better fit. In all of the models the effect of an increase in wages on costs is positive and significant, in keeping with expectations and theory. All of the variables were normalized by dividing at their sample mean such that we can interpret the regression coefficients as elasticities at the mean.

5.1. *Economies of Scale.* After controlling for wages, region and year effects, and the institute type, the measures of economies of scale calculated from the estimated parameters are all much less than 1 and significantly so (Table 4). The estimates of *SCE* for wheat institutes range from 0.22 to 0.26; those for maize institutes range from 0.14 to 0.32. The results imply that, at the mean levels of research output and other explanatory variables, strong economies of scale exist for both wheat and maize institutes. If output increases by 10%, costs would increase no more than 3.2%. Evidence of such strong economies of scale from the multivariate analysis is consistent with the descriptive evidence and reflects the patterns in Figure 1. The elasticities of cost with respect to output are relatively small compared with those found in studies of nonprofit institutions (i.e., 0.70–0.90 for public education institutions from de Groot et al., 1991, and Cohn et al., 1989; and 0.60–0.83 for hospitals from Cowing and Holtmann, 1983, and Fournier and Mitchell, 1992).

The strong economies of scale are largely unchanged when we control for other institutional factors. Comparing results in Tables 4 and 5, after controlling for the four *Z* factors and their interactions with output, the *SCE* elasticities still fall in a similar range (0.27 for wheat institutes; from 0.29 to 0.32 for maize institutes). Although the coefficients on variables representing several of the institutional factors are significant and suggest that there are other ways to affect breeding efficiency (the discussion of which is deferred to the next section), the remarkably low and highly significant measures of *SCE* indicate that significant cost savings could be attained if the scale of China's breeding institutions were expanded.

Accounting for a number of the potential econometric problems does not significantly alter the magnitude or significance of the measures of economies of scale, as can be seen in Table 6. To address concerns of measurement error, exclusion restriction tests of the validity of our demand-side IVs show that they meet the statistical criteria required for identification. Using these IVs and the 3SLS estimator does not substantively change the estimates of the economies of scale parameters. The economies of scale parameters range from 0.12 to 0.26. The results hold for both wheat and maize in both the base model and the full model. Allowing for lags of different lengths or controlling for the unobserved heterogeneity also does not materially affect the estimates of economies of scale.[12] Similar to the results generated by the parameter estimates of the single-output cost function, results based

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[12] Results are not affected after models are corrected for potential autocorrelation and heteroskedasticity. The results are also robust over the choice of functional form. The coefficients of economies (or ray economies) of scale obtained from the translog cost function are very close to those obtained originally.

TABLE 7

RAY ECONOMIES OF SCALE AND ECONOMIES OF SCOPE BASED ON ESTIMATION OF THE MULTIPLE-OUTPUT COST FUNCTION OF WHEAT AND MAIZE VARIETY PRODUCTION

Model Specification	Ray Economies of Scale (SCE^{ray})[a]	Economies of Scope (SOE)[b]
Base model	0.33***	−0.099
	(24.93)	[−0.098, −0.103]
Human capital	0.33***	−0.050
	(23.30)	[−0.049, −0.055]
Spill-in variable	0.35***	−0.083
	(23.28)	[−0.080, −0.086]
Spill-in + human capital	0.38***	−0.038
	(21.09)	[−0.035, −0.042]
Full model	0.39***	−0.010
	(20.01)	[−0.003, −0.011]

[a] The measure of ray economies of scale is calculated using Equation (5). Numbers in parentheses are the absolute values of t-statistics for the test of null hypothesis that the coefficient of economies of scale is equal to 1 (versus less than 1).

[b] The measure of economies of scope is calculated using Equation (5). The mean and confidence interval of the scope coefficient were generated by bootstrapping; 400 samples with replacement were implemented. The number on the top of each cell is the mean, whereas the two numbers below it refer to the lower and upper bounds of a 95% confidence interval.

on the multiple-output cost function also imply high and statistically significant estimates of ray economies of scale. The estimates of SOE^{ray}, which range from 0.33 to 0.39, mean that if wheat and maize institutes doubled their output of both wheat and maize varieties, the total variable cost of wheat and maize breeding would increase by only 33–39%. The strong ray economies of scale are also not affected by alternative estimation strategies or model specifications.

5.2. *Economies of Scope.* Although not as strong or as robust as the evidence of economies of scale, our multiple-output cost function models show the existence of economies of scope between wheat and maize variety production, as summarized in Table 7. The estimates of SOE based on the parameter estimates of the base model indicate that there would be cost saving of about 10% if a wheat-only and maize-only breeding institute were combined into a joint wheat–maize institute. Bootstrapped confidence intervals show that the measured elasticities are statistically significantly different from 0. Unlike economies of scale, however, economies of scope are affected when other institutional factors are added. For example, if we control for the educational level (or human capital) of breeders, the cost savings from merging wheat and maize institutes drops from 10% to 5%, and it drops to only 3.8% when both human capital and spill-in variables are added to the model.

5.3. *Other Institutional Characteristics.* In addition to the cost efficiency associated with the scale and scope of wheat and maize variety production, the statistical analysis supports the early descriptive findings and shows that economic efficiency is also affected by other institutional variables, as can be seen in Table 5. For example, except for one case, the coefficients on the interaction between breeder's education and output are negative and statistically significant. The magnitudes of the coefficients show that if research managers can increase the share of breeders with college and more education by 10% (for the average institute this means the addition of about one college-educated breeder), the marginal cost will fall by around 1.0%.

An increase in the proportion of genetic material used in breeding that comes from outside the province also increases efficiency (by reducing costs). If breeders can increase their imported genetic materials by 10%, the marginal cost of wheat (or maize) variety production will fall by 2.2% (or 1.3%).[13] Such an effect, a type of spill-in, has long been known to play an important role in the effectiveness of spending on agricultural research (Pardey et al., 1991; McCalla, 1994; Byerlee and Traxler, 2001; Johnson and Evenson, 1999; Alston, 2002). Our study demonstrates that spill-ins are also an important source of efficiency gains at the level of the crop-breeding institute, and policies and institutions that facilitate the free flow of germ plasm will raise the productivity of the agricultural research system.

Compared with increasing an institute's human capital and access to genetic material, the effects of having scientists from other disciplines and the burden of caring for retirees are less clear. Having scientists from other disciplines in a breeding program marginally reduces wheat-breeding costs. It has the opposite effect (though small) in maize institutes, although the effect disappears in estimations that correct for measurement error. Hence, at the very least, it seems that the addition of soil scientists, plant pathologists, and other scientists does not significantly detract from productivity, even in the types of breeding centers that dominate China's research system.

Our findings also do not provide evidence that would validate the complaints of scientists and research administrators about the adverse effects of bearing the burden of the welfare of retirees. Although this result is surprising (since almost every research administrator complains about such welfare obligations), it could be that there are two offsetting effects of having breeders remaining formally attached to the institute after they retire. Although retirees probably do take away resources that could otherwise be used for research, their presence could be an asset—since they have experience, breeding material inventory, and contacts in the seed system—which could help reduce costs.

6. SUMMARY AND CONCLUSION

Agricultural science in the public domain is increasingly being asked to do more with less. The scientists responsible for breeding new varieties today will have to

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[13] This estimate is based on a local linear approximation, evaluated at the sample mean. A referee pointed out that the spillover relationship is unlikely to be linear—larger effects when the use of external materials is low. In most of the empirical studies that have looked at the issue, and over the range of data in this study, a linear approximation is reasonable, because the programs are generally in a similar part of the (low end of the) range of use of imported material.

meet even greater challenges than those that gave rise to the Green Revolution of the 1970s and 1980s. In an era of waning support and increased demands for output, it will be necessary to become increasingly efficient at producing new varieties. However, there is almost no empirically based evidence to guide the efforts of reorganizing the current agricultural research system. In this study, we attempt to identify sources of efficiency in China's crop-breeding system. Using panel data on 46 wheat- and maize-breeding institutes from 1981 to 2000, we examine the factors that affect the variable costs of wheat and maize varieties. Using a number of approaches and accounting for a number of econometric issues, our analysis produces a set of robust results that can help guide reformers in their efforts to increase the efficiency of China's crop-breeding system.

Our most striking finding, and one that is relevant for crop-breeding centers around the world, is the existence of strong economies of scale in China's crop-breeding research. The coefficients of economies of scale imply a significant cost saving associated with expanding the scale of crop-breeding institutes. According to our findings, the current large number of small crop-breeding institutes is the main source of inefficiency. In addition, a number of other sources of inefficiency are identified. Though not as strong or consistent as the results for economies of scale, we find there are economies of scope in the production of varieties of different crops. Merging a wheat-only institute with a maize-only institute can lead to small, but significant cost savings. We also find that raising the human capital of the breeding staff and facilitating the access of breeders to wider sources of germ plasm increases the efficiency of breeding. All of these results fit squarely with our expectations based on knowledge of the crop-breeding system in China as well as from a consideration of the counterpart institutions in other countries and in international agricultural research centers.

Taken at face value, our findings can support a blueprint for the reform of crop breeding in developing countries, from a system dominated by a multitude of small, fragmented and isolated breeding stations to one characterized by a smaller number of "super" breeding centers. New centers would be larger, broader in scope, and staffed by well-trained scientists representing a number of different agricultural science disciplines. Expanding the size of the institutes, either by merging two or more or by expanding a single institute and shutting down others, would take advantage of the strong economies of scale. Our results do not give exact guidance on how big the institutes should be, in part because we are not observing many institutes that have reached or passed the minimum of the average cost curve. However, even casual observation of the descriptive data shows that crop-breeding institutes can be expanded by at least several times their current size. Such a move would start to shift the size of breeding programs in China more toward those of developed nations.

The new centers could also take advantage of other sources of efficiency gains. The positive economies of scope mean that the new super centers (at least in northern China) should have at least two departments, one for wheat and one for maize. It also can be argued that new departments should be created in the centers for the support of work by scientists from other disciplines. Although we did not always find strong efficiency gains from the addition of other scientists, there was even less evidence of any diseconomies associated with institutes that contained nonbreeders.[14] But, in anticipation of future changes in the technology of crop breeding that surely will confront any modern agricultural research system (e.g., the increasing importance of biotechnology and precision agriculture), it is likely that there will be substantial gains to having an institutional structure in place that can take advantage of and develop its own high technology products.

However, a number of factors potentially could undermine part or even all of these efficiencies, should the government implement an approach based on merging and expanding smaller crop-breeding institutes into a smaller number of super breeding centers. First, there will be nonpecuniary costs associated with mergers or expansions. For instance, researchers who are likely to lose their jobs and directors who are likely to lose their political positions will do whatever they can to prevent any ambitious reorganization from happening. The more ambitious the reform is, the greater will be the opposition. Second, merging or cutting will encounter transaction costs associated with the reform process itself and with reorganizing operations of merged or expanded institutes. Finally, a smaller number of super stations could mean less competition, leaving less incentive for innovative research. Hence, in deciding how to implement a reorganization of the crop-breeding research system, research sector leaders should also take into account these adverse factors and potential transactions costs.

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[14] Although we expected to find that the presence of agricultural scientists from other disciplines would enhance the efficiency of crop breeding, we found no evidence that they do in China's crop-breeding institutes. We can suggest a number of possible explanations. One is that although these scientists add to the breeding effort, they do not contribute enough to cover the additional costs they impose. More likely is that China's breeding centers institutionally are not set up to facilitate productive interactions among scientists from different disciplines. In fact, in interviews with crop-breeding center research administrators and scientists, we were frequently told that accounting practices, office layouts, and the norms of science in China discourage cross-disciplinary interaction among scientists in many crop-breeding institutes.

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