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Comparison of Breeding and Cultural Contribution to Yield Gains of Korean Rice

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ABSTRACT: Analysis of breeding gains in grain yield has been intensively conducted in wheat, barley, oat, maize, and soybean. Such information is limited in rice. The objective of this study was to compare the breeding gains and cultural gains contributed to yield gains of Korean rice varieties since early 1900s. Two sets of yield data were used for analysis; the historical yield data of 1908 for old japonica cultivars, and present yield data in the years from 1996 to 1998 for the six cultivars, consisting of previous two old cultivars and four contemporary cultivars. The old cultivars were two native cultivars, Jodongi and Damageum, while contemporary cultivars were two premium quality japonica cultivars, Hwaseongbyeo and Dongjinbyeo, and two Tongil-type cultivars, high yielding cultivars developed from indica/japonica hybridization, Milyang23 and Dasanbyeo. The yield differences of old cultivars between the experiments in 1908 and the experiments from 1996 to 1998 were estimated as cultural gains (1.84 tons ha^{-1}) due to the improvement of cultivation technology. Yield differences between the old cultivars and contemporary cultivars were considered total yield gains during the periods. These were 2.51 tons ha^{-1} for japonica cultivars and 3.81 tons ha^{-1} for Tongil-type cultivars. From these data, the genetic gain of 0.67 tons ha^{-1} and 1.97 tons ha^{-1} were estimated for japonica cultivars and Tongil-type cultivars respectively. The ratio between cultural gain and genetic gain appeared to be 2.7:1 for japonica cultivars and 1:1 for Tongil-type cultivars. This analysis clearly showed the higher genetic contribution in Tongil-type cultivars than in japonica cultivars, suggesting a guideline to be used when planning new yield improvement programs. Additional implication has emerged when a better yield response to modern cultivation technology was found in one of the old cultivars, suggesting the combined improvement between breeding and cultural improvement is necessary for attaining the maximum yield capacity of a crop.

Keywords : rice, yield gain, genetic gain, cultural gain

During the last century rice productivity in Korea has increased continuously as a result of the adoption of modern cultivars, increased investments in irrigation, and greater use of fertilizer. However, the trend of continuous increase of productivity will be uncertain in future because production environment is projected to be very different. Expansion of cultivated area is limited, investments in irrigation have virtually ceased, high fertilizer use is causing concern for environmental pollution, and rice lands are being lost to non-rice uses in the major rice-growing areas (Peng *et al.*, 2000). Although a linear model often provides the best fit when used to project crop yield a few years into the future, it is not fit for extrapolation of crop yield to the far distant future (Specht *et al.*, 1984). Despite these difficulties and uncertainties, it is still important for crop research community to know the future prospect of yield increase, so the future strategies of crop research and improvement will be directed based on this prospect.

Yield increases must be divided into genetic gains and cultural gains (Schmidt, 1984). In the latter, cultivation technologies such as appropriate tillage, fertilizer, herbicide, and disease and insect control are included. Genetic improvement in grain yield has been intensively studied in wheat, barley, oat, and maize (Austin *et al.*, 1980; Wych and Rasmusson, 1983; Wych and Stuthman, 1983; Tollenaar, 1989; Feil, 1984). Along with these time course of genetic improvements, comparison was made between genetic and cultural contribution to yield gains in many major crop species. In the United States, the genetic contributions of total yield increase were 39% for sorghum, 71 % for maize, 80% for soybean, 52% for wheat, and 17% for cotton. (Miller and Kebede, 1984; Duvick, 1984; Specht and Williams, 1984; Schmidt, 1984; Meredith and Bridge, 1984). This kind of information was reported in Korea though the information they provided was limited. Park *et al.* (1990) conducted an experiment with six rice cultivars, subjected to four chronological cultivation methods in which 52% of yield increase was attributed to cultivar improvement. Kwon (1987), in a experiment with eight cultivars with four chronological cultivation methods, reported 43% of total yield gain was allocated to the cultivar improvement. As shown in cases of Kwons and Parks studies, different estimations from different researchers using different data simulations showed

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many controversial results. For example, Jensen (1978) stated that the total gain in wheat productivity could be divided nearly equally between technology and genetics while Heug (1980) estimated the range of 26 to 29% resulted directly from breeding for yield. This inconsistency might have come from the differences in methods and cultivars they adopted for analysis, and/or incorporation of environmental factors in which the experiment and analysis were conducted.

For increasing yield, the development of the high-yielding cultivars as well as best fitting agronomic and management practices are needed concurrently. However, as a farm economists points of view, the best option is to develop cultivars with higher yield potential through crop improvement rather than the best-fitting cultivation technologies which would be, inevitably, a high-input farming. We have to know the portions of breeding contribution which could be relatively easily controlled, compared to other environmental factors such as radiation, disease and insect pests. Such information is limited in Korean rice. The objective of this study was to compare the breeding gains and cultural gains contributed to yield gains of Korean rice since beginning of 1900s. Through this analysis, establishment of a guide line for future breeding strategies to determine the priority of investment between development of best cultivars versus development of best-fitting cultivation technology could be achieved.

MATERIALS AND METHODS

A total of six cultivars were analyzed in this experiment (Table 1). Jodongji and Damageum are old cultivars, grown before 1908. They are late-maturing type japonica cultivars and became widely cultivated cultivars at the first half of the 20^{th} century in Korea. The historical yield data of two old cultivars was obtained from the yield records of 1908 at the Demonstration Plot of National Crop Experiment Station.

A separate three-year (1996-1998) field experiment was conducted with six cultivars, the two old cultivars and four representative contemporary cultivars developed after 1976. Hwaseongbyeo and Dongjinbyeo were premium-quality japonica cultivars, while Milyang23 and Dasanbyeo were Tongil-type cultivars with high-yielding potential developed from progenies of wide hybridization between indica and japonica parent cultivars (Moon *et al.*, 1998).

The cultivation practices were subjected to the Rural Development Administration Experimental Guidelines (Rural Development Administration 2000). Thirty-day-old seedlings were transplanted on May 25 of every experimental year. Hill spacing was 0.15 by 0.30 m with three seedlings per hill. The fertilizer application was done with the rate of 110 Kg ha^{-1} of nitrogen, 70 Kg ha^{-1} of phosphorus, and 80 Kg ha^{-1} of potassium. Phosphorus and potassium were applied and incorporated in all plots 1 d before transplanting while nitrogen was applied in four splits (basal, at mid-tillering, at panicle initiation, and at flowering) to ensure N sufficiency for all entries. Weeds were controlled with herbicides and hand weeding.

Each of the 20 plants were measured for their culm length and yield components, i.e., panicle number per hill, spikelet number per panicle, total and grain filling rate, and 1000 grain weight. Grain yield was determined from 100 plants for each plot and adjusted to moisture content of 0.14 g H_2O g^{-1} fresh weight.

RESULTS AND DISCUSSION

Yield components

The yield components for each cultivar were measured during the 1996-1998 field experiments (Table 2). There was no significant difference in panicle number, spikelet number and grain weight between old and contemporary japonica cultivars. The significant grain filling rate was found to be improved in japonica cultivars; 15% higher in contemporary japonica cultivars compared to those of old japonica cultivars. However, the comparison between japonica and Tongil-type cultivars showed different patterns in yield component changes. Less panicle numbers and more

Table 1. Genetic backgrounds and agronomic characters of rice cultivars analyzed.

Cultivar	Cross	Year	Heading habit	Plant height	Remarks
Jodongji	Pure-line selection	1900s	Medium	Tall	Old japonica
Damageum	Pure-line selection	1900s	Late	Very tall	Old japonica
Hwaseongbyeo	Aichi37/Samnammbyeo	1985	Medium	Medium-tall	Contemporary Japonica
Dongjinbyeo	HR1276/Sadominori	1981	Late	Medium-tall	Contemporary japonica
Milyang23	Suwon231/IR24	1976	Medium	Short	Tongil-type*
Dasanbyeo	Suwon332/Suwon333	1995	Early	Short	Improved Tongil-type

*Tongil-type cultivar: Korean-bred rice cultivars derived from indica/japonica hybridization

Table 2. Mean values of yield components of the six rice cultivars in the year from 1996 to 1998. Data are indicated as Mean±standard deviation.

Cultivars	Panicle number per hill	Spikelet number per panicle	Grain filling grain rate (%)	Grain weight (g/1000 grains)
Jodongji	14.7±2.4	92±10.0	70±17.0	21.8±1.5
Damageum	13.2±1.3	83±19.0	73±18.0	21.1±1.5
Dongjinbyeo	14.3±1.5	92±20.0	86±13.0	22.2±1.0
Hwaseongbyeo	14.5±2.7	85±11.0	81±14.0	21.4±1.2
Milyang23	13.0±1.6	117±33.0	78±17.0	20.9±1.4
Dasanbyeo	12.8±0.9	123±20.0	79±10.0	23.0±1.0

Table 3. Brown rice yields of six rice cultivars at the National Crop Experiment Station Demonstration Plot from 1996 to 1998. Jodongji and Damageum are old cultivars, while Hwaseongbyeo and Dongjinbyeo are premium quality contemporary japonica cultivars bred in 1980s. Milyang23 and Dasanbyeo are representative Tongil-type cultivars, developed from wide crosses between japonica and indica cutivars after 1970.

Classification	Cultivars	Brown rice yields (tons/ha^{-1})			
		1996	1997	1998	Mean±S.E
Old Japonica	Jodongji	5.74	5.64	5.05	5.47±0.21
	Damageum	4.60	4.25	4.81	4.55±0.16
	Mean	5.17	4.95	4.93	5.01±0.17
Contemporary Japonica	Hwaseongbyeo	5.15	5.81	5.56	5.51±0.19
	Dongjinbyeo	6.14	5.96	5.50	5.88±0.19
	Mean	5.65	5.89	5.53	5.69±0.11
Contemporary Tongil-type	Milyang23	7.41	6.78	6.46	6.86±0.27
	Dasanbyeo	6.51	7.91	6.88	7.10±0.41
	Mean	6.96	7.35	6.67	6.99±0.19

spikelet numbers are the unique characteristics of high-yielding cultivars (Table 2). Significantly increased number of spikelets was observed in Tongil-type cultivars; 30-40 % increase compared to japonica cultivars. Additionally, improved Tongil-type cultivar, Dasanbyeo showed a significant increase in grain weight (from 20.9 gram of Milyang23 to 23.0 gram of Dasanbyeo). From the data shown in this study, the yield increase in japonica cultivars may be due to the increase in grain filling rate, while that of the Tongil-type cultivars was from increased spikelet number combined with heavier 1000-grain-weight. The increased sink size may be one of the main reasons that a more rapid progress in yield increase was observed in Tongil-type cultivars than in japonica cultivars. Functions of each yield components contributed to yield increase are beyond the scope of this study so that more discussion is reserved for future researches.

Comparison of breeding and cultural contribution

The cultural gain was estimated by the equation as follows: *Cultural gain (tons ha^{-1})=Mean yield of two old cultivars during 1996-19981908-Mean yield of old cultivars in 1908*

The mean brown rice yields of two old japonica cultivars in 1908 was 3.18 tons ha^{-1}; mean of 3.06 tons ha^{1} for Jodongji and 3.30 tons ha^{-1} for Damageum (Fig. 1). That of present time (1996-1998) was 5.02 tons ha^{-1}; 5.48 tons ha^{-1} for Jodongji and 4.55 tons ha^{-1} for Damageum.

It seemed that the mean yield differences of the old cultivars between 1908 and 1996-1998 were due to cultural gains contributed from technical improvement. From the equation, cultural gain of old cultivars was 1.84 tons ha^{-1}; mean of 2.42 tons ha^{-1} for Jodongji and 1.25 tons ha^{-1} for Damageum at present time (1996-1998). Cultural gain of 1.84 tons ha^{-1} deduced from the old japonica cultivars was applied to other calculation for contemporary cultivars used in this analysis.

For the estimation of breeding gain, following equation was used : *Breeding gain (tons ha^{-1})=Total gains ($Yield_A$ $Yield_B$) Cultural gain*

where $Yiled_A$ denotes mean yield during 1996-1998 for contemporary cultivars, and $Yield_B$ denotes the yield in 1908 for old cultivars, and mean cultural gains of old cultivars was 1.84 tons ha^{-1}. The mean yields of contemporary japonica and Tongil-type cultivars during 1996-1998 were 5.69 and 6.99

tons ha^{-1}, respectively (Table 3). From yield of contemporary cultivars, yield of old cultivarsin 1908 was subtracted to get the total gains during the periods (Table 4). Resulting total gains was subtracted by cultural gain of 1.84 tons ha^{-1} to get breeding gains of respective cultivars (0.49, 0.86, 1.84, and 2.08 tons ha^{-1} for Hwaseongbyeo, Dongjinbyeo, Milyang 23,

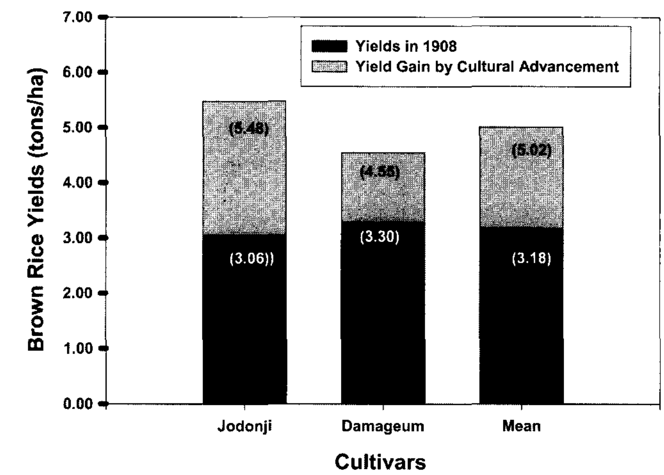

Fig. 1. Brown rice yields of old cultivars for evaluation of cultural gain (stack bars with gray color) is calculated by subtracting yields in 1908 (lower stack bars with black color) from total yields (number in parenthesis) of three years in 1996, 1997 and 1998.

and Dasanbyeo, respectively). These values are compared to cultural gains (1.84 tons ha^{-1}) to get contribution rate (Fig. 2).

There was a significant difference in breeding contribution between japonica cultivars and Tongil-type cultivar groups. In japonica cultivars, breeding contribution was only 26.8%, lower than that of 51.8% in Tongil-type cultivars (Fig. 2). Even though a significant positive correlation was observed between total yields and breeding contribution both within

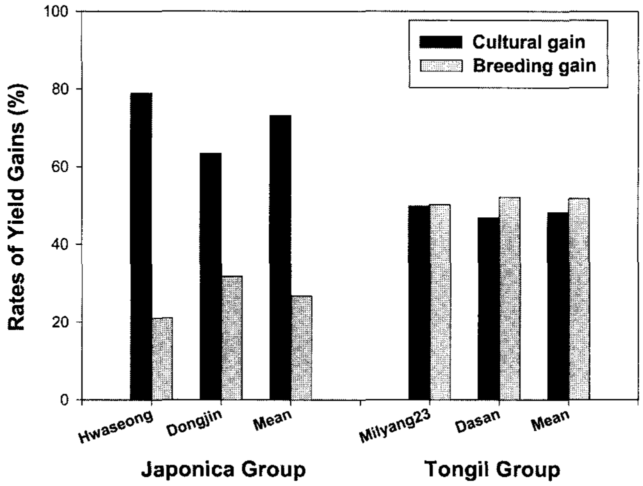

Fig. 2. Comparison of portions of cultural and breeding gains contributed to total yield gains of rice in Korea.

Table 4. Breeding gains of contemporary cultivars, estimated from the yield data of old Korean rice cultivars, Jodonggi and Damageum. Unit is tons ha^{-1}.

Cultivars	Yield of modern cultivars during 1996-1998	Mean yield of old cultivars in 1908	Total gains	Breeding gains
Hwaseongbyeo	5.51	3.18	2.33	0.49
Dongjinbyeo	5.88	3.18	2.70	0.86
Mean	5.69	3.18	2.51	0.67
Milyang23	6.86	3.18	3.68	1.84
Dasanbyeo	7.10	3.18	3.92	2.08
Mean	6.99	3.18	3.81	1.97

Table 5. Comparison of contributions in breeding and cultural gains between two old cultivars, Jodongji and Damageum. Unit is tons ha^{-1}.

Cultivars	Jodongji			Damageum		
	Total gain	Cultural gain	Breeding gain	Total Gain	Cultural gain	Breeding gain
Hwaseongbyeo	2.447	2.417	0.030	2.207	1.253	0.954
Dongjinbyeo	2.807	2.417	0.390	2.567	1.253	1.314
Mean	2.627	2.417	0.210	2.387	1.253	1.134
Milyang 23	3.807	2.417	1.390	3.567	1.253	2.314
Dasanbyeo	4.043	2.417	1.626	3.803	1.253	2.550
Mean	3.925	2.417	1.508	3.685	1.253	2.432

and between cultivar groups, the observed breeding contribution in this experiment was lower than that of previous reports. Park *et al.* (1990) reported 52% of breeding contribution in rice, and Kwon (1987) reported 43% of breeding contribution to rice yield improvement in Korea. This inconsistency again revealed the difficulties to evaluate breeding contribution to yield gains on total basis. The contribution rate could be fluctuated by many factors such as the environmental conditions in which the experiments were conducted, and use of specific cultivars. The example of fluctuation in breeding contribution was greatly changed depending on cultivars used for analysis (Table 5). Damageum showed greater breeding contribution than that of Jodongji. From these observations, it is needed to contrive new modeling system to define exact cont ribution rates of breeding versus cultivation to establish a guideline for technical and breeding improvement for yields.

In this experiment, a greater breeding gain was observed in Tongil-type cultivars compared to japonica cultivars, which may imply that it is more desirable to introduce germplasm with wide genetic distance to achieve higher yields. This is confirmed by the following observation. Several research groups addressed questions on how much of the annual improvement in soybean yield is attributable to genetic technology in the USA during the late 1970s and early 1980s. Among them, Specht and Williams (1984) observed that their initial estimate of 18.8 kg ha^{-1} yr^{-1} was about 80% of the 23.7 kg ha^{-1} yr^{-1} rate of yield improvement. However, they also noted a major discontinuity in the 75-yr yield trend line. Regression analyses conducted with cultivars of hybridization origin (mostly post-1943 releases) versus those conducted with cultivars of plant introduction origin (mostly pre-1943 releases) revealed substantially different y-intercept values. The intersection of these two regression lines in the year 1943 revealed that the former group of cultivars had an absolute yield advantage of 25%. This "quantum jump" in the genetic yield improvement resulted when breeders shifted from plant introduction to hybridization as their means for developing and releasing new cultivars, thereby expanding the genetic variance available to them for selection. This happened during Tongil-type cultivar development in Korea, with substantial introduction of wide genetic variation through introduction of indica germplasm.

In this experiment, limited data availability prevented us from using the other formulae to estimate breeding gains of yields such as formulae used for uniform nursery yield data (Schmidt, 1984) and formulae for crop yield versus time data (Specht *et al,* 1999). The new equation was created for the analysis of this experiment that could use all possibly available data in this experiment. However, the best-fitting model for the equation is not examined so that further examination is need in experiments with diverse cultivars and environmental condition. Also, a specially designed experiments to compare the adequacy of this equation with other formulae are needed in future. The inconsistency in rate of breeding gains between present and previous reports (Kwon, 1987; Park *et al.,* 1990) may be attributed to limited use of the cultivars developed in 1980s instead of the use of the cultivars developed in 1990s. Considering the large leap in japonica cultivar yield during end of 1980s and 1990s, the breeding gain may be increased to present calculation of 27% for japonica cultivars. Conclusively, a comprehensive and specially designed experiment is need to evaluate the adequacy of equation suggested in this manuscript and responses of different cultivars developed in different time table.

Suggestion for yield improvement

Although separation of yield gains to breeding and cultural gains is difficult to define and measure unambiguously, it has proved to be a useful concept whose analysis has provided impetus to crop modeling and to thinking about yield determination. A very simple analysis used in the present study illustrated an important principle that the maximum yield could be achieved through concurrent improvements in breeding and cultivation technologies. One of the old cultivarsJodongji gained more yields by technical improvement (Table 5). The higher breeding gains were achieved in Tongil-type cultivars. The combined efforts for improvement in cultivation technology following the Jodongji model and improvement in cultivars following Tongil-type cultivar model may be a desirable strategy to achieve maximum yield potentials in rice. However, a prior study to define which factor contributed the best should be conducted to improve the factor defined with concentration.

As an example, introduction of semi-dwarfing genes in rice and wheat that initially sought for resistance to lodging with heavier dressings of fertilizer N, their advantage for yield potential was then realized progressively through improved partitioning to the components of yield. Moreover, the higher level of N availability also made selection for increased chlorophyll and rubisco content in wheat, and longer stay green in maize was possible, raising the yield potential still further. The same principle could be applied to the improvement of the many agronomic and management practices that have contributed to yield improvement, earlier planting, narrower rows, better weed control, and lower post-harvest losses. In addition to these, a final caution should be taken about yield difference between experiments and farmers level. Reducing the large gap that exists between the yield possible in agricultural research plots, and that actually realized on the farmers level might require more emphasis on agricultural economy and convenience of farm management.

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