Quality-Oriented Technical Change in Japanese Wheat Breeding

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Abstract: The article presents a productivity analysis of Japanese Wheat Breeding research. Given recent policy change, wheat breeders may breed high quality, i.e. high protein content, wheat. We regard breeding research as multi-output process, and examine breeding program with output distance function. Also, we will analyze the effect of gene recharge rate on breeding productivity, and withdraw the policy implication for property rights.

Key Words: Wheat Breeding Research, Induced Innovation, Wheat Quality, Gene Recharge

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Japanese consumers pay close attention to food quality in wheat as well as in other products. The quality of wheat imported to Japan is regarded by Japanese as superior to that of domestic wheat. Millers frequently have urged Japanese wheat growers and breeders to produce a better-quality product. Changes in government wheat price policy now are adding teeth to those appeals. Until 2000, the General Food Policy Bureau paid a fixed price for all domestically produced wheat, regardless of quality. Since 2000, wheat purchase prices have been linked to quality, so that farm revenues have become sensitive to product quality. Farmers' exclusive preference for high-yielding wheat varieties therefore has given way to an interest in quality as well.

Wheat quality enhancements, such as enrichments in protein content, are determined largely by genetic factors and thus breeding research. Genetic improvements are regarded by most crop scientists to be potentially more effective than farming practices in boosting wheat quality characteristics. The rising focus on grain quality therefore has encouraged greater attention to wheat breeding efforts.

In the present paper, we specify breeding research as a knowledge-based production process in which each new wheat variety is the result of a particular development strategy. Insofar as it is a productive process, breeding research is subject to technological change. Technological change is partly random but responds as well to explicit or implicit product prices.

A higher premium on high-protein wheat boosts the output price of a unit of protein relative to the (sometimes implicit) price of per-are yield [1]. That alone should serve to redirect breeding resources toward wheat varieties that are protein-rich and thus toward protein-favoring technical change. Binswanger (1978) has shown that research resources can be allocated efficiently only if the bias of technological change favors the good with the higher relative price. A useful way of depicting such induced innovation is to characterize technical progress in terms of shifts in product transformation curves, defined not on the quantities of goods but on the quantity or other measure of their characteristics.

Breeding research, not only in wheat but in rice or many other grains, has been the subject of extensive study. Most studies estimate breeding success in terms of a single output, such as a boost in the yield response to nitrogen applications (Traxler and Byerlee 1993, Sakiura 1984). However, Japanese wheat breeding research has pursued multiple goals such as quantity (yield) as well as quality characteristics. As far as we know, no studies have yet considered quality characteristics, along with yield, as a research output. We do so here by specifying breeding research as a multi-output process.

Analytical Framework

Induced Innovation

The notion of induced innovation has long been used to analyze changes in input

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[1] An “are” is a tenth of a hectare, that is 10m x 10m or one hundred square meters.

combinations induced by changes in relative input prices. It is employed extensively in agricultural productivity analysis. Binswanger (1978) has, in addition, examined changes in output combinations induced by output price changes. We apply this output version of induced innovation to wheat breeding research, and in particular to the case of two outputs: quality and quantity.

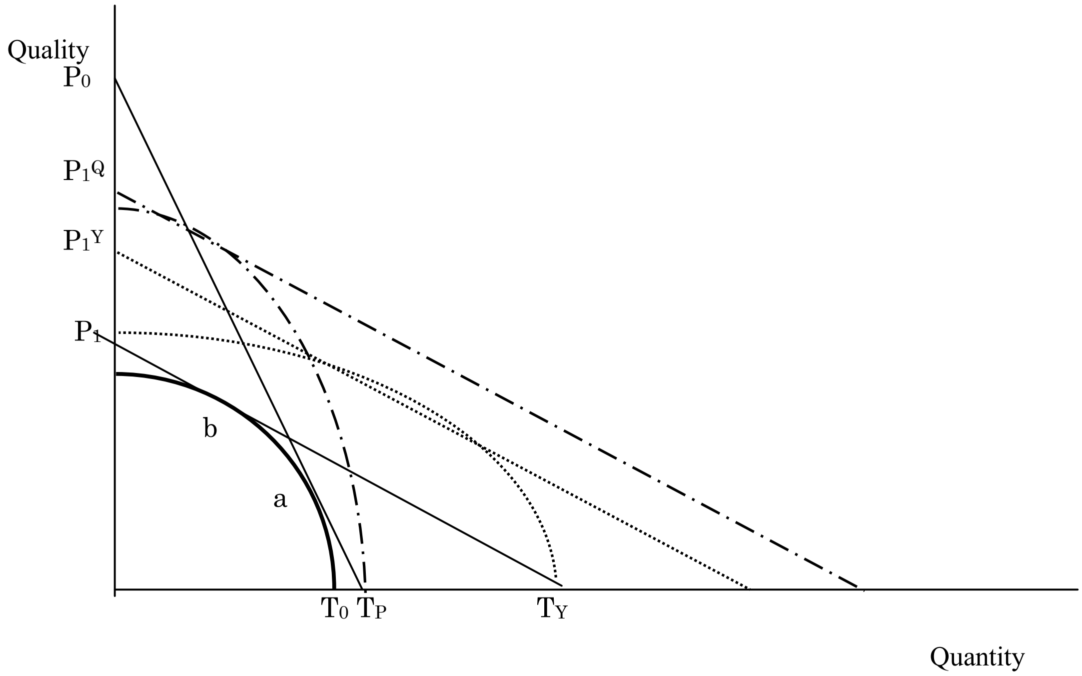

Figure 1. Technological change in Breeding research

The Japanese government's decision to link wheat price to wheat quality induces the production of high-quality wheat, especially with a high protein content, by pricing protein higher than it had been priced before. In particular, the policy change encourages wheat farmers to plant relatively high quality varieties (HQVs), and urges breeders to develop those varieties.

This process is traced by the two steps indicated in Figure 1. Production possibility frontiers (PPFs) of wheat quality (percent protein content) and wheat quantity (per-are yield) are depicted. T_0, T_P, and T_Y are PPFs, and P_1, P_1^Y and P_1^Q represent price ratios. At original price ratio P_0, breeders develop wheat varieties such as indicated at point *a* on T_0, which are relatively high-yielding (HYVs). After the policy-change, the (implicit) price ratio becomes P_1, where, under original research technology $T_{0,}$ breeding research is directed toward the wheat varieties at point *b*. We now allow non-neutral technical change to occur in biological research technology, shifting research PPFs outward in a biased or nonparallel manner. Holding relative price constant at P_1, the PPF may shift in two alternative directions: toward quantity-favoring direction T_Y, or quality-favoring direction T_P.

If both possible shifts were to occur at the same rate, the potential revenue gain would be to P_1^Y in the case of quantity-oriented innovation, or to P_1^P in the case of quality-oriented innovation. Because P_1^P is greater than P_1^Y, it is rational for the research institute to allocate its resources toward developing the high-quality varieties (HQVs). That is, research resources are allocated efficiently only if the bias of technological change favors the good with the higher relative price (Binswanger 1978). We apply such logic to wheat characteristics.

Multi-Output Case

A transformation function of wheat breeding research might be characterized as

(1) $$G\left(Y,P,L,SY,t\right)=0$$

where Y, P, L are research outputs representing per-are yield, percentage protein content, and centimeters of straw length. SY is research input expressed in scientist-years, namely the total number of scientists engaged in the development of a given variety, and t is a technology shift parameter represented by the year in which the variety is registered. Because, however, our data are drawn from field experiment results, we also record the per-are quantity N of nitrogen applied, dummy variables CM indicating cultivation methods such as ridge width or additional nitrogen use, and dummy variables Di for geographic location and wheat type. We then can expand equation (1) as

(2) $$G\left(Y, P, L, SY, t, N, Di, CM\right) = 0$$

One reason breeding-research PPFs shift is that genes are introduced, in what is sometimes called *recharge* (Evenson 1998). We use variety pedigree data to construct a variable ($gene$) representing the rate at which the genetic resources available to breeders are recharged from sources outside the breeder's home area. Incorporating that factor, our breeding technology model becomes

(3) $$G\left(Y, P, L, SY, t, N, Di, CM, gene\right) = 0 .$$

Reliable data on research investment stocks were unavailable and inputs are consequently measured here as flows.

Output Distance Function

We use output distance functions to express the set of technological opportunities at a wheat research laboratories' disposal. Our approach therefore may be regarded as an output version of that in Irz and Thirtle (2004). In such context, output distance function D_O is defined on the proportionate distances at which wheat research laboratories operate, in their production of wheat characteristics, from the boundaries of the technological opportunities at their disposal. Thus Do = 1 corresponds to situations in which laboratories are completely technically efficient, that is operate at the frontiers of their output possibility sets $P(x)$ (Färe and Primont 1995). Letting x be the input vector and y the output vector, we have

$$(4) \quad D_O(x,y) = \inf\{\theta > 0 : (y/\theta) \in P(x)\}$$

Duality between the output distance and revenue functions, representing the set of revenue-maximizing output possibilities, is written as

$$(5) \quad \begin{array}{l} R(x,r) = \max\{ry : D_O(x,y) \leq 1\}, r \in \Re_+^M \\ D_O(x,y) = \sup\{ry : R(x,r) \leq 1\}, y \in \Re_+^M \end{array}$$

where r is a vector of output prices. Output distance, and thus the set of boundary possibilities of wheat characteristics, generally is a function of technology variable t. The revenue maximization problem implies that the shadow price of output, namely the first derivative of (4) with respect to a specific wheat characteristic, is derived as

$$(6) \quad \frac{\partial D_o\left(x, y^*\left(r,x,t\right)\right)}{\partial y_m} = \frac{r_m}{R\left(r,x,t\right)}$$

That is, the shadow price of output y_m is the revenue-deflated output price. This revenue deflator is a function of the market price of the given wheat characteristic. In the absence of such prices, one may consider the ratio of two characteristics' shadow prices:

$$(7)\quad \frac{r_m}{r_{m'}} = \frac{\partial D_O\left(x,y,t\right)/\partial y_m}{\partial D_O\left(x,y,t\right)/\partial y_{m'}},\ m \neq m'$$

Expressing shadow price derivative (6) in elasticity terms permits us to obtain the revenue share of the given characteristic m of actual revenue R:

$$(8)\quad \varepsilon_{D_O,y_m} = \frac{\partial \ln D_O}{\partial \ln y_m} = \frac{r_m \cdot y_m}{R\left(r,x,t\right)} = S_m$$

By the same token, the first derivative of the output distance function with respect to a particular laboratory input is

$$(9)\quad \varepsilon_{D_O,xk} = \frac{\partial \ln D_O}{\partial \ln x_k} = -\frac{\partial \ln R\left(r,x,t\right)}{\partial \ln x_k}.$$

The derivative of the output distance function with respect to any laboratory input is the negative of the derivative of the revenue function with respect to that input. Equations (8) and (9) are respectively positive and negative in order for monotonicity to hold. [2]

Technological Change

The rate of technological change is found by differentiating equation (1) with respect to t:

$$(10)\quad \varepsilon_{D_O,t} = \frac{\partial \ln D_O\left(x,y,t\right)}{\partial t} = -\frac{\partial \ln R\left(r,x,t\right)}{\partial t}.$$

The derivative of the output distance function with respect to t is, in elasticity form, the negative of

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[2] More precisely, we require that $\partial D/\partial y > 0, \partial D/\partial x < 0$.

the revenue elasticity with respect to t, providing a primal measure of technological change. The elasticity is negative (positive) if technological change is progressive (regressive).

Further differentiating (8) with respect to t gives a measure of technological change bias:

$$(11) \quad B_{m\cdot t} = \frac{\partial \ln S_m}{\partial t} .$$

It signifies the extent to which the PPF's slope changes along a given diagonal from the origin as technical improvement shifts the PPF outward, so that, at a constant output price ratio, the laboratory would produce more of the characteristic toward which the PPF has tilted. If $B_{m\cdot t}$ is positive (negative), the PPF shifts toward (away from) characteristic y_m, so that technological change is y_m - favoring (-disfavoring). The difference between the m^{th} and l^{th} characteristic's bias measure represents the technology-change-induced shift in the ratio of the characteristics' magnitudes when the corresponding price ratio is constant.

Recharge Rate

Our particular interest is in estimating the effect of the gene recharge rate on the wheat laboratory's rate of technological change. The derivative of output distance function (4) with respect to the recharge rate is

$$(13) \quad \frac{\partial \ln D_O}{\partial gene} = -\frac{\partial \ln R}{\partial gene}$$

that is, the negative of the associated revenue boost. When this parameter is negative (positive), an increased recharge rate contributes to technological progress (regress).

Empirical Specification

Model

We specify a translog functional form for the output distance function. The translog is desirable because it not only is flexible but easily used to impose linear homogeneity in outputs. It has frequently been used in empirical studies such as Grosskopf *et al.* (1995b), Coelli and Perelman (1999), and Brümmer *et al.* (2002).

We estimate the translog output distance function parametrically. Dependent variable D_O is set to 1.0, implying Japanese wheat research laboratories operate on the boundary of the set of technically efficient possibilities. Restricted OLS is employed to impose output homogeneity (Grosskopf, Hayes, and Hirschberg 1995a). [3] Incorporating our discussion of equation (3), we have

$$\begin{aligned}\ln D_O &= \alpha_0 + \sum_{m=1}^{3} \alpha_m \ln y_m + \frac{1}{2}\sum_{l=1}^{3}\sum_{m=1}^{3} \alpha_{lm} \ln y_l \ln y_m \\ &+ \sum_{k=1}^{2} \beta_k \ln x_k + \frac{1}{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \beta_{jk} \ln x_j \ln x_k + \frac{1}{2}\sum_{m=1}^{3}\sum_{k=1}^{2} \gamma_{mk} \ln y_m \ln x_k \\ &+ \sum_{i=1}^{4} \delta_{it} t \cdot D_i + \sum_{i=1}^{4}\sum_{m=1}^{3} \delta_{imt} \ln y_m t \cdot D_i + \frac{1}{2}\sum_{i=1}^{4} \delta_{i\,tt} t^2 \cdot D_i + \delta_{gene}\, gene + \sum_{c=1}^{2} \delta_c\, cm\end{aligned}$$

where $\alpha, \beta, \gamma, \delta$ are the parameters to be estimated. In this expression, $\{ y_{l,} y_m \}$ is the vector of output characteristics ($y =$ yield in kilograms per are, $l =$ straw length in centimeters, $p =$ % protein content), and x_j, x_k is a vector of inputs ($sy =$ scientist years, $n =$ nitrogen applied in kilograms per are), and t is time. D_i is the dummy variable representing planting location and

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[3] We earlier estimated the model with stochastic frontier analysis (SFA), permitting research technologies to be inefficient. However, results seriously violated regularity conditions such as monotonicity in input and convexity in outputs.

wheat type (D_{HS} =Hokkaido Standard wheat, D_{HH} = Hokkaido Hard wheat, D_{FS} =Fuken[4] Standard wheat, and D_{FH} =Fuken Hard wheat), and *gene* is the gene recharge rate. We include two dummy variables to represent cultivation methods: CM, corresponding respectively to whether additional nitrogen was applied ($CM = B$), and whether the narrow-ridge planting method was employed ($CM = R$) or not employed.

Linear homogeneity in wheat characteristics and symmetry of the quadratic form (Young's theorem) are imposed by requiring respectively that $\sum_{m=1}^{3}\alpha_m = 1$, $\sum_{m=1}^{3}\alpha_{lm} = \sum_{m=1}^{3}\gamma_{mk} = \sum_{m=1}^{3}\delta_{imt} = 0$ and $\alpha_{lm} = \alpha_{ml}, \beta_{jk} = \beta_{kj}$. In addition to monotonicity, convexity in outputs (Färe and Primont 1995, O'Donnell and Coelli 2005) would reasonably hold if the research laboratory can readily develop convex combinations of the characteristics of current varieties.

Data

All released wheat varieties in Japan are registered with the Japanese Government. They are listed by year of registration, each variety accompanied with details of its experimental trials (Ministry of Agriculture, Forestry, and Fisheries). Descriptive statistics are given in Table 1.

Standard wheat varieties bring higher yields than do hard varieties but tend to have a lower protein content. More generally, larger grain kernels provide lower protein content per kernel than do smaller kernels. On account of the influence of the semi-dwarf gene, shorter

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[4] Hokkaido is located in the far north of Japan. Fuken represents all remaining regions except Tokyo.

straw lengths often bring higher yields than do longer straw lengths. However, while this holds true in Fuken, it does not necessarily hold in Hokkaido. According to Nonaka (1985), present Hokkaido straw lengths appear to be optimal for the harvesting machinery employed, so that any straw length reduction would complicate harvesting. In any event, since sometime in the 1980s, breeding research has turned away from attempting further reductions in straw length despite the likelihood of per-are yield improvements in some regions.

Gene Resources and Breeding Productivity

Effects of gene resources or genetic diversity on agricultural production, and in particular on yield stability, have been assessed in several studies (Evenson and Gollin 1997; Smale, Hartell, and Senauer 1998). Diversifying gene resources tends to enhance yields' means while stabilizing their variability. At the same time, gene recharge is the key element in this gene diversification process and thus in technological improvement (Evenson 1998). Thus, focusing on the gene recharge rate is an important way of representing gene resource conditions in the laboratory.

Recharge Rate

Breeding research is a consecutive process of introducing new gene materials. However, parent wheats vary in their genetic relatedness or similarity, depending principally on the geographic areas from which the strains have been introduced. For instance some parent genes are drawn from foreign countries, others from neighboring Japanese research stations or from the researcher's own station. We assume in this study a one-one relationship between locational difference and genetic dissimilarity.

To estimate genes' effect on wheat breeding research, we constructed a gene recharge rate. We first defined a variety's *historical gene exchange area* by examining the coefficient of parentage (COP) of each variety pair. The examination showed that Hokkaido varieties are quite distinct from those at other (Fuken) Japanese experiment stations. At the same time, varieties at Fuken stations are comparatively similar to one another. On the basis of such analysis, we specified three historical of gene exchange areas in Japan: Hokkaido Standard, Hokkaido Hard, and Fuken Standard. Genes introduced from outside of these historical areas are considered to contribute to recharge.

The recharge (*gene*) variable itself is constructed by considering each variety's four preceding generations. We compute the proportion of parents in each of these four generations whose genetic material is drawn from outside the variety's historical gene exchange area. The proportions are then averaged over the four generations, weighted by the generation's distance from the variety examined. Gene recharge rates therefore range between zero and one. Sample means of the Japanese wheat varieties' gene recharge rates are presented in Table 1.

Empirical Results

Parameter estimates are shown in Table 2 and regularity conditions checked in Table 3. All regularity conditions are met at all data means. Monotonicity is satisfied at sample mean in all four wheat-type models. Convexity in outputs is satisfied at all means except in the Fuken Hard.

Technological Change

Table 4 gives our estimates of technological change rates in Japanese wheat breeding, computed from equation (10). Because negative (positive) signs indicate technological progress (regress), Table 4 indicates breeding technology improvements have expanded the wheat variety possibilities producible from a given set of research resources

Both in Hokkaido and Fuken, research technology progress has been slightly greater in Standard wheats than in Hard wheats. The Standard wheat category, used mainly in the Japanese noodle *udon*, includes numerous local varieties. Farmer's began breeding these varieties long before national breeding programs were launched. The rich stock of varieties resulting from such informal breeding has contributed to strong subsequent advances in formal breeding programs.

Hard wheats, used mainly in bread baking, are not indigenous to Japan, and Japanese hard-wheat breeding was first launched in Hokkaido. Hard-wheat breeding attempts in Fuken have begun only recently, employing parents strains from Hokkaido and foreign countries. Because Fuken has the comparative advantage of exploiting earlier gene stocks from Hokkaido, Fuken hard wheats recently have improved more rapidly than have Hokkaido hard wheats.

Influence of Gene Recharge Rate

Our estimate of δ_{gene} in table 2, reflecting the effect of a higher gene recharge rate on the range of wheat varieties producible with given research inputs, is -0.143 and statistically highly significant (t = - 4.49). Introducing genetic material from foreign countries or another Japanese gene exchange area positively contributes to technical change, enhancing the combinations of protein, straw length, and yield characteristics achievable with given research resources. Maintaining easy access to foreign gene sources is essential to Japanese wheat breeding progress.

Bias of Technological Change

Technological change biases computed from equation (11) are shown in table 5, evaluated at the sample means of each wheat type. Except in Fuken Hard wheats, technical improvement in Japanese wheat breeding laboratories has been protein favoring, straw length disfavoring, and yield disfavoring. Wheat characteristic or variety possibility frontiers, that is, achievable with a given set of laboratory resources have shifted toward protein and away from straw length and per-are yield. We find the recent bias toward longer straw lengths puzzling and are continuing to examine this topic. The bias toward protein, however, is consistent with rising preference for – and implicit consumer prices of – protein. Japanese Government wheat breeding laboratories have, in this sense, been sensitive to consumer demand despite their not-for-profit status.

This argument is reinforced by observing how protein's shadow prices have changed relative to the shadow prices of straw length and yield (total wheat quantity). The induced innovation theory discussed above suggests observed technological change biases in table 5 should respond to increases in the relative implicit market price of protein. We confirm this hypothesis by computing those shadow price ratios on the basis of equation (8). Results are presented in table 6. As predicted, the yield-to-protein shadow price ratios (r_Y / r_P) have trended downward during the 32-year sample period for all wheat varieties except Fuken Hard. That is, shadow prices of protein have risen relative to shadow prices of quantity as expressed in per-are yield. Changes in Japanese wheat breeding strategy again appear to have been largely induced by market demand changes.

Conclusions

Recent policy changes in Japan linking wheat quality and price have stimulated wheat breeding programs that have better allocated breeding resources to wheat quality characteristics. An output version of induced innovation theory would suggest in such context that breeding successes should shift toward the product characteristics whose relative prices are rising.

To test such an hypothesis, we have exploited the fact that an output distance function may be used to represent the combinations of wheat characteristics that Japanese wheat breeding programs can achieve in a given technological state. Rates at which wheat characteristics are traded off on the frontier of this set (that is, shadow prices) ought, for a revenue-maximizing breeding program, to be equated to corresponding ratios of the wheat characteristics' actual or implicit market prices. Thus, if observed shadow prices appear to be shifting in the same direction as relative market prices, we have evidence that breeding programs in Japanese Government laboratories have been responding to market forces, and in particular acting in a way consistent with maximizing the revenues achievable with a given set of breeding resources.

Parametric results drawn from a translog form of the output distance function show that technical change in Japanese breeding has in recent years indeed favored protein over other wheat characteristics. Holding relative prices fixed, the wheat characteristics transformation curve has shifted toward protein and away from both per-are yield and straw length. Japanese wheat breeding laboratories therefore have responded rationally to government price-policy changes, even though laboratories operate in the public sector and hence do not benefit from profit incentives.

We have captured the effects of gene resources on breeding research success by employing what we call a gene recharge rate, namely the rate at which genes from non-traditional locations are introduced into Japanese breeding programs. We find that higher gene recharge rates significantly enhance technological change in wheat breeding, measured as the rate at which the wheat characteristics combinations achievable with a given set of research resources is shifted outward. It is particularly important for Japanese wheat breeders, therefore, to maintain wide gene-recharge areas, a goal best met if access to new genetic material is facilitated and research exemptions provided for gene property rights.

Table 1. Means and Standard Deviations of Wheat Characteristics, Research Input, and Recharge rate in Hokkaido and Fuken.

Variables	All Data	Hokkaido		Fuken	
		Standard	Hard	Standard	Hard
n	436	190	92	116	38
Yield (kg/a)	49.8	57.2	40.1	47.4	43.4
	(13.54)	(12.03)	(7.88)	(12.93)	(12.82)
Straw Length (cm)	89.8	94.1	90.1	83.6	86.5
	(9.05)	(7.22)	(8.59)	(7.11)	(11.52)
Protein Content (%)	10.7	9.9	12.8	9.6	12.8
	(2.05)	(1.53)	(0.94)	(1.82)	(1.74)
Scientist Year	55.5	52.1	60.9	56.0	58.5
(number of scientist × year)	(15.03)	(12.19)	(5.58)	(19.21)	(23.04)
Nitrogen (kg/a)	0.95	1.03	1.06	0.80	0.75
	(0.38)	(0.36)	(0.43)	(0.30)	(0.29)
Recharge rate	0.61979	0.59	0.57	0.69	0.68
	(0.224)	(0.184)	(0.175)	(0.270)	(0.289)

Source : Experimental result for registration published by each variety.

Note : Mean values with standard deviations in parentheses.

Table 2. Distance Function Parameter Estimates

Parameter	Estimate	t-ratio		Parameter	Estimate	t-ratio	
α_0	-0.639	-0.59		$\delta_{DHS\,t}$	-0.001	-0.16	
α_Y	-0.310	-1.10		$\delta_{DHS\,Yt}$	-0.006	-1.46	
α_L	-0.117	-0.48		$\delta_{DHS\,Pt}$	0.015	3.49	**
α_P	1.427	3.76	**	$\delta_{DHS\,Lt}$	-0.010	-3.47	**
β_N	0.181	0.70		$\delta_{DHS\,tt}$	0.0004	3.09	**
β_{SY}	-0.672	-1.40		$\delta_{DHH\,t}$	-0.009	-1.29	
α_{YY}	0.253	4.80	**	$\delta_{DHH\,Yt}$	-0.003	-0.96	
α_{YL}	-0.066	-1.10		$\delta_{DHH\,Pt}$	0.014	2.56	**
α_{YP}	-0.187	-2.18	**	$\delta_{DHH\,Lt}$	-0.011	-2.65	**
α_{LL}	0.339	6.42	**	$\delta_{DHH\,tt}$	0.0004	4.59	**
α_{LP}	-0.273	-3.88	**	$\delta_{DFS\,t}$	-0.015	-3.60	**
α_{PP}	0.460	3.35	**	$\delta_{DFS\,Yt}$	-0.003	-1.38	
β_{NN}	-0.097	-2.25	**	$\delta_{DFS\,Pt}$	0.011	3.70	**
β_{NSY}	-0.063	-1.06		$\delta_{DFS\,Lt}$	-0.008	-3.65	**
β_{SYSY}	0.095	0.85		$\delta_{DFS\,tt}$	0.001	6.10	**
γ_{YN}	-0.154	-2.10	**	$\delta_{DFH\,t}$	0.024	1.58	
γ_{LN}	0.279	4.43	**	$\delta_{DFH\,Yt}$	0.002	1.25	
γ_{PN}	-0.125	-1.41		$\delta_{DFH\,Pt}$	0.0003	0.11	
γ_{YSY}	0.165	1.32		$\delta_{DFH\,Lt}$	-0.003	-1.46	
γ_{LSY}	0.176	1.68	*	$\delta_{DFH\,tt}$	-0.001	-2.26	**
γ_{PSY}	-0.341	-2.18	**	δ_{gene}	-0.143	-4.49	**
				δ_{DB}	-0.037	-2.10	**
				δ_{DR}	-0.110	-5.44	**

Table 3. Theoretical Properties of Estimated Output Distance Function

		All-Data	Hokkaido		Fuken	
		Mean	Standard	Hard	Standard	Hard
Monotonicity	$\partial \ln D/\partial \ln Y$					
	Mean	0.26	0.30	0.19	0.26	0.38
	% negative		0.00	2.17	2.59	0.00
	$\partial \ln D/\partial \ln L$					
	Mean	0.25	0.25	0.32	0.30	0.32
	% negative		0.53	2.17	0.86	0.00
	$\partial \ln D/\partial \ln P$					
	Mean	0.49	0.45	0.61	0.44	0.31
	% negative		0.00	0.00	0.00	0.00
	$\partial \ln D/\partial \ln SY$					
	Mean	-0.07	-0.07	-0.12	-0.03	-0.09
	% positive		7.37	0.00	31.90	0.00
	Convexity in outputs	satisfied	satisfied at mean	satisfied at mean	satisfied at mean	violated at mean
	% violated		7.90	2.17	14.66	47.37

Table 4. Technological Change Rate

Location	Wheat type	$\varepsilon_{D\cdot t}$
Hokkaido	Standard (*HS*)	-0.098
	Hard (*HH*)	-0.093
Fuken	Standard (*FS*)	-0.114
	Hard (*FH*)	-0.108

Note: Computed from equation (10).

Table 5. Bias of Technological Change

Location	Wheat type	Yield (Y) B_{Yt}	Straw Length (L) B_{Lt}	Protein Content (P) B_{Pt}
Hokkaido	Standard (*HS*)	-0.018	-0.039	0.034
	Hard (*HH*)	-0.016	-0.054	0.023
Fuken	Standard (*FS*)	-0.012	-0.027	0.025
	Hard (*FH*)	0.0063	-0.008	0.001

Note: Computed from equation (11).

Table 6. Shdow Price Ratios

Year	Variety Number	r_Y/r_P	r_Y/r_L	r_P/r_L	Year	Variety Number	r_Y/r_P	r_Y/r_L	r_P/r_L
Hokkaido Standard					Fuken Standard				
1968	108	0.164	6.014	36.44	1975	119	0.941	1.698	1.80
1974	114	0.161	2.286	14.10	1983	128	0.130	1.405	10.62
1974	115	0.124	2.103	16.62	1988	132	0.193	1.784	9.45
1981	126	0.117	1.534	13.29	1988	133	0.104	0.996	9.51
1990	136	0.091	1.485	16.68	1989	134	0.119	1.027	8.81
1995	142	0.076	1.620	21.58	1990	135	0.201	1.639	8.30
2000	149	0.063	1.518	24.20	1992	137	0.113	2.028	17.89
Hokkaido Hard					1992	138	0.101	0.710	6.86
1965	104	0.181	6.297	34.87	1993	140	0.104	0.805	7.54
1985	130	0.101	1.369	13.72	1993	141	0.069	1.251	17.71
1993	139	0.084	2.123	25.08	1995	144	0.076	1.090	14.05
2000	150	0.063	2.244	35.40	1999	145	0.083	1.350	16.04
Fuken Hard					1999	147	0.092	4.645	49.80
1999	146	0.351	2.333	6.63	2000	152	0.064	1.417	22.29
2001	153	0.284	2.955	10.47	2002	156	0.087	1.659	18.91
2002	155	0.315	2.959	9.26	2005	163	0.072	4.422	61.07
2002	157	0.652	1.948	3.02	2005	164	0.076	1.648	21.08
2003	160	0.580	1.435	2.44					

Note: Computed from equation (7).

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