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Quality-Oriented Technical Change in Japanese Wheat Breeding

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Abstract: The article presents a productivity analysis of Japanese wheat breeding research. We first estimate an hedonic function to determine the marginal implicit values of Japanese wheat characteristics and find that protein contributes substantially to millers' price offers to farmers. Induced innovation theory implies breeders thus should be responding to new protein-oriented price policies by developing high-protein wheat varieties. We test this hypothesis by estimating a distance function relating breeding resources – including what we call gene-recharge rates – to the yield and protein characteristics of discovered varieties. New varieties indeed have been protein-favoring and yield-disfavoring, suggesting government research programs have been market-oriented.

Key Words: Wheat Breeding Research, Induced Innovation, Wheat Quality, Gene Recharge
JEL codes: Q16, O32, O13

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1. Introduction

The induced-innovation hypothesis – that the direction of invention is influenced by the relative values of the potentially innovated characteristics – usually is expressed in terms of the invention-adopter's total factor employment. Innovators seek to reduce the adopter's total cost by improving one of the adopter's factors in a way that comparatively saves the higher priced of its other inputs (Binswanger, 1978a; Ruttan et al., 1978). Rising relative labor wages, for example, induced discovery of the mechanical harvester, in turn boosting the quantity of farm capital relative to labor and the amount of labor for which a unit of capital could substitute.

With many inventions, especially mechanical and logistical ones intended to reduce cost at given output, such focus on the adopter's relative factor employment is useful. With other inventions, particularly of a material input intended to improve the quality of the adopter's outputs, it is, as Evenson (1998) shows, more insightful to express innovation incentives in terms of the inventor's own technology. Inventors in such a framework seek to boost the demand for the adopter's products by enhancing in a key material input the characteristics the adopter's customers value most highly. Thus, breeders develop banana rootstock yielding larger rather than sweeter bananas if farmers' customers reveal, in the prices they pay, a preference for size over sweetness. Testing the induced innovation hypothesis in this latter context involves observing the rootstock characteristics which breeders try to or succeed in developing with given breeding resources, then matching such characteristics to those for which food consumers are willing to pay.

In the present paper we consider a remarkable instance of the latter, quality-oriented technical change: improvements in Japanese wheat strains. We first assess changes in consumers' effective demands for wheat characteristics, then match them to changes in the combinations of wheat seed characteristics that Japanese breeders have, with given research resources, succeeded in offering to farmers. Broadly speaking, the induced innovation hypothesis is satisfied to the extent breeders' resource-constrained successes are consistent with wheat consumers' tastes. However, demonstrating such correlations for quality-enhancing innovations is not as straightforward as it is for cost-reducing ones, a fact likely responsible for the far greater frequency of cost-type than quality-type innovation studies. In the former, the analyst looks for signs that, for example, farm capital-labor quantity ratios are caused by capital-labor price ratios, controlling for substitutions farmers could effect through management practices alone, that is in the absence of technical innovation (e.g., Thirtle, et al., 2002). Data of that sort are readily available in capital and labor markets. In contrast, consumer preferences for product quality, and associated seed characteristics which breeders can offer given their resource constraints, are virtual and can be assessed only hedonically.

In the Japanese wheat industry, a natural experiment fortunately is available for the latter purposes. Until 2000, the Japanese General Food Policy Bureau paid Japanese farmers a single price per ton regardless of grain quality, and domestic millers were required to accept those wheats regardless of their disfavored qualities. Since then, premia and discounts have been incorporated for certain quality characteristics in order to provide farmers an incentive to produce wheat with the preferred characteristics. Yet wheat quality enhancements, such as protein enrichment, are determined largely by genetic rather than farm management practices. Farmers as well as millers, therefore, have had an incentive to lobby the Japanese government's wheat research program to breed for the higher-valued characteristics. If government breeders have responded adequately to this pressure, we should observe their new varieties to embed comparatively higher amounts of the preferred characteristics than did the older varieties. Furthermore, because virtual prices of the newly favored characteristics have risen relative to those of the newly disfavored ones, we should find that breeders are allocating resources in such a way that more of the disfavored characteristic is given up per unit of the favored characteristic than was the case in 2000 (Binswanger, 1978b, p. 109).[1] Klerkx and Leeuwis (2008) investigate the extent to which farmers' research demands are reflected in the science projects funded through farmer levies. They conclude that, because of the involvement of multiple stakeholders, farmer interests are inadequately taken into consideration.

Most studies of breeding success have been conducted in terms of a single characteristic, such as yield response to nitrogen application (Traxler and Byerlee, 1993; Sakiura, 1984). Our own focus will be on two important wheat characteristics: protein percentage and mean per-hectare yield, the former influencing product quality and thus consumer price, and the latter influencing per-ton farm cost. The virtual price farmers are willing to pay for either of these wheat-seed characteristics is the premium they will pay for a variety that contains one unit more of it but that in all other respects is identical to a base variety. Yield characteristics were important to farmers well before the 2000 price-policy reform, while protein percentage could become important only after the premium/discount system was introduced. Thus, the virtual price of protein should after 1999 have risen relative to the virtual price of per-hectare yield, redirecting breeding resources toward protein-rich varieties and thus toward protein-favoring technical change.

To examine this hypothesis, we specify breeding research as a knowledge-based production process in which each new variety is the result of a development program. Because breeding is productive, it is itself subject to technical change. A useful way of testing for price-induced varietal innovation therefore is to characterize technical progress as shifts in breeders' *innovation possibility curves*, namely combinations of – in the present case – protein and mean yield which breeders can achieve with a fixed endowment of breeding resources. Breeders move from one variety, and thus one protein-yield combination, to another along an innovation possibility curve by launching new development programs and dropping old ones. Curves shift outward if breeding technology is improved, for example through new methods of inserting genetic material (Evenson, 1998). Tradeoff rates between protein content and mean-yield can, in response to changes in their virtual prices, be influenced by the direction of the laboratory's overall development strategy. Both the level and the tradeoff rates of an innovation possibilities set depend greatly on the genetic information breeders employ, especially from novel sources. Evenson (1998) has used "recharge," and Simpson and Sedjo (1998) and others "biodiversity," to describe the quantity and quality of such newly introduced genetic material. We develop a new metric for the recharge rate and gauge its impacts on Japanese wheat breeding.

We find that effective Japanese demand for wheat protein has risen substantially in recent years and that Japanese wheat breeders have responded by developing protein-rich varieties. Productivity in the use of given breeding resources has been rising, and in ways that, comparatively speaking, are protein-favoring and yield-disfavoring. The mean per-hectare yield given up on Japan's innovation possibility frontier to achieve an additional unit of wheat protein also has been rising, consistent with a revenue-maximizing breeder faced with rising relative protein prices. Japan's National Agricultural Research Center has, despite its public status, therefore responded to price changes in ways consistent with market forces. Salter and Martin (2001) review econometric evidence of the economic benefits of publicly funded basic research, concluding that benefits in the form of new knowledge, methods, and problem-solving are substantial.

2. Policy History

On account of the popularity of western-style eating habits, Japanese wheat consumption has been rising and rice consumption falling for the past 40 years. Eighty-five percent of the wheat consumed in Japan is now from foreign sources. Yet domestic wheat remains important both in the consumer food mix and in the farm economy.

The Standard wheat category, used mainly in *udon* noodles, includes many local varieties that farmers began breeding long before 1926, when government breeding programs were launched. The consequently rich local variety stock has contributed greatly to state breeding successes. Hard wheats, used primarily in bread, instead were introduced from outside Japan and national breeding efforts in their direction first launched in Hokkaido. The first hard or bread wheat was released in Hokkaido in 1930, but its development was then discontinued until the1960's. Breeding of hard wheats in Japan's Fuken (non-Hokkaido) regions began only in the 1990's, employing both Hokkaido and foreign parents. Because Fuken laboratories have been able to exploit earlier Hokkaido stocks, their hard wheats have improved more rapidly than have Hokkaido's hard wheats.

The institutional history of Japan's wheat breeding is similar to that of its rice breeding (Akino and Hayami, 1975). The scientific breeding era, launched in 1926, can be divided into two periods. During the first, 1926 to 1950, crossbreeding methods were newly introduced into the country. Wheat strains were first crossed at the central government breeding station, then distributed to regional stations for adaptation to local agronomic environments. As cross-breeding skills accumulated and diffused, regional stations began creating their own crosses. Seventy new wheat varieties were developed during this first period despite the infancy of Japan's cross-breeding technology.

During the second period, 1951 to the present, eight national breeding research stations (later integrated into five) and two local government experiment stations were developed and 90 new wheat varieties introduced. The first three decades of this period corresponded to the era of modern Japanese economic growth. The government's main breeding goal was to produce strains complementing the rapid farm mechanization which then was substituting machinery for labor. Emphasis was placed on, for example, a variety's adaptability to machine planting and harvesting, lodging tolerance, and disease resistance. In the early 1980's, farmers were shifting from rice to wheat in response to the rice acreage restriction program launched in 1970. Although domestic wheat production rose dramatically, its quality was much less suitable to Japan's principal demand – for noodles and bread – than were foreign wheats. Japanese grain millers began urging domestic breeders and farmers to produce wheats with protein, amylo, and other characteristics equivalent to the foreign product. The emphasis on wheat quality had begun.

In addition to millers' appeals, the government began in 2000 to exert its own wheat-quality pressure through the schedule of prices that millers were permitted to pay farmers. Until 2000, wheat prices at the miller level were determined entirely by government. A bid system was then introduced allowing millers to offer their own prices based on quality, subject to remaining within 95% and 105% of the previous year's price. (The permissible range was widened in 2005 to 93% and 107%.) As Figure 1 shows, miller wheat prices began immediately to diverge according to variety, reflecting the milling and baking characteristics those varieties typically provided. Hokkaido wheat varieties, represented in Figure 1 by the broken lines, have increasingly brought the highest prices on account of their high protein. Farmer revenues now are influenced by the variety and quality of the wheat produced, so that quality, and particularly protein content, appears to be the critical breeding goal. Our analysis focuses on this increasingly quality-oriented period.

[Figure 1]

3. Analytical Framework

To document the rising Japanese preference for wheat protein, we first fit a hedonic function to post-1999 wheat prices. The hedonic model takes the form (Ladd and Martin, 1976; Stiegert and Blanc, 1997)

$$\begin{aligned} \ln w_{jrt} = \beta_0 + \beta_1 \ln pro_{jrt} + \beta_2 \ln ash_{jrt} + \beta_3 \ln clr_{jrt} \\ + \beta_4 \ln aml_{jrt} + \beta_5 \ln wgt_{jrt} + \beta_6 hard_j + \varepsilon_{jrt}. \end{aligned} \tag{1}$$

where *j* refers to variety, *r* to region, and *t* to year; w_{jrt} is wheat price, *pro* is protein percentage, *ash* is ash percentage (related to flour color), *clr* is color grader value (in which a lower value indicates a higher flour brightness), *aml* is an indicator of flour stickiness, *wgt* is weight or kernel solidity, *hard* indicates whether the wheat is a hard variety, and ε_{jrt} is the residual.[2] Planted-year dummies also are incorporated to take weather conditions into account. Wheat quality and thus post-2000 price are expected to be related positively to protein, amylo, and hardness, and negatively to ash content and color.

If wheat innovation has been price-induced, it should not only have produced higher-protein strains but boosted the tradeoff between protein-oriented and yield-oriented characteristics. Price-responsive shifts in breeding innovation possibility frontiers (IPFs) are depicted in Figure 2, where wheat quality (represented by protein content) and wheat quantity (per-hectare yield) are indicated on the two axes. T_0, T_P, and T_Y are alternative IPFs, and P_0, P_1, P_1^P, and P_1^Y are alternative ratios of the virtual price of a given quality characteristic to the virtual price of quantity or per-hectare yield. Points on IPFs assume particular farm management regimes, such as planting times and fertilizer rates. Tangent to these points, and on the interiors of and more convex than the IPFs, are what may be called *management possibility curves*, representing characteristics combinations produced with a given wheat variety and given management program.

At original characteristics price ratio P_0, where grain quality is relatively weakly valued in the grower's wheat price schedule and hence in the demand for varietal characteristics, breeders optimally develop the high-yielding (HYV) strains indicated at point *a* on T_0. Grower lobbying would, in the face of the post-1999 wheat price schedule providing an increasing reward for protein content, have shifted the virtual price ratio to P_1, that is in which the value of the protein characteristic rises relative to the quantity characteristic. In the short run, that is under original research technology T_0, revenue-maximizing breeders would have redirected their search efforts toward the varietal characteristics at point *b*. In the longer run, research technology can be changed by, for example, introducing exotic genetic material boosting the varietal potential at breeders' disposal.

The long-run change can be non-neutral, shifting the IPF in a biased or nonparallel way. Two biases are alternatively possible: toward a quantity-favoring IPF (T_Y) or a quality-favoring (T_P) one. As long as the post-1999 wheat price structure is maintained, maximum breeder revenues lie along P_1^Y if research technology shifts in the quantity-oriented direction, and along P_1^P if it shifts in the quality-oriented direction. Because P_1^P revenues exceed P_1^Y revenues, the rational choice is to develop the high-quality varieties (HQVs) shown on Figure 2's dot-dashed line. That is, research resources are allocated efficiently only if the technical change bias moves in the direction of the characteristic with the rising relative price (Binswanger, 1978a, p. 109).

3.1. *Modeling Breeding Technology*

The breeding research transformation functions depicted in Figure 2 might generally be specified as

$$(2) \qquad G\left(\mathbf{C},\ \mathbf{K}_{Hum},\ \mathbf{K}_{Gen},\ \mathbf{M},\ t\right) = 0$$

where **C** is the output vector of the relevant varietal characteristics; $\mathbf{K}_{Hum}$ is the vector of human capital available at breeding laboratories during the time interval in which the variety was being developed, and hence reflecting the lag between the variety's development and its registration; $\mathbf{K}_{Gen}$ is the genetic information available to breeders; **M** the farm management practices employed in producing the grain; and *t* is the year of the variety's registration, reflecting technology shifts not captured in $\mathbf{K}_{Hum}$ and $\mathbf{K}_{Gen}$.[3] $\mathbf{K}_{Hum}$ Rather than estimate the transformation functions themselves, we follow the normal practice of casting technology in terms of the proportional distance to frontier (2) from a given varietal discovery, then restricting the distance to unity so that the variety's characteristics lie on frontier (2) itself.[4] Such a distance function is an output version of, for example, the one in Irz and Thirtle (2004).

In particular, let characteristics vector $\mathbf{C}$ in equation (1) be comprised of {*P*, *Y*}, where *P* is the wheat's percentage protein content and *Y* its mean per-hectare yield, and let **x** represent input vector $\{\mathbf{K}_{Hum}, \mathbf{K}_{Gen}, \mathbf{M}\}$. For given inputs **x**, the output distance D_O of a given wheat characteristics combination **C** is

$$(3) \qquad D_O(\mathbf{C}, \mathbf{x}, t) = \inf\{\theta > 0 : (\mathbf{C}/\theta) \in P(\mathbf{x}, t)\} = \sup_{\mathbf{r}}\{\mathbf{rC}/R(\mathbf{x}, \mathbf{r}, t)\}$$

where **r** is the 2 x 1 vector of virtual prices of characteristics {P, Y}, $P(\mathbf{x}, t)$ is the producible output set corresponding to equation (2), and $R(\mathbf{r}, \mathbf{x}, t)$ is the revenue function. Maximizing **C**'s distance, at given factor levels and breeding technology, maximizes the breeder's virtual revenue at given virtual prices **r** (Färe and Primont, 1995). Setting $D_O(\mathbf{C}, \mathbf{x}, t)\,\varepsilon = 1$, where ε is a multiplicative error, depicts situations in which laboratories are technically efficient, that is operate at the characteristics boundary *G* at their disposal given resources **x** and breeding technology *t*.

The percentage rate of technical change is found by log-differentiating (3) with respect to t:

(4) $$\varepsilon_{D_O,\,t} \;=\; \frac{\partial \ln D_O\left(\mathbf{C},\mathbf{x},t\right)}{\partial t} \;=\; -\frac{\partial \ln R\left(\mathbf{r},\mathbf{x},t\right)}{\partial t}.$$

The proportional distance change is the negative of the proportional revenue change because, when a given variety occupies a successively smaller portion of the distance to the characteristics frontier, that frontier must be expanding and maximal revenues therefore rising. The technical change elasticity thus is negative (positive) if technology change is progressive (regressive).

The revenue maximization problem implies that, if the m^{th} characteristic's market price is r_m, its corresponding shadow price – namely its opportunity cost in terms of other characteristics impaired or additional inputs required – can be written as (Irz and Thirtle, 2004; Färe and Primont, 1995)

(5) $$\frac{\partial D_o\left[\mathbf{C}^*\left(\mathbf{r},\,\mathbf{x},\,t\right),\,\mathbf{x},\,t\right]}{\partial C_m} \;=\; \frac{r_m}{R\left(\mathbf{r},\mathbf{x},\,t\right)}$$

In the revenue-maximizing solution, characteristic C_m's shadow price is equated to its revenue-deflated market price. Because Japanese wheat breeding is conducted in government laboratories, so that characteristics do not have market prices at the breeder level, we will be particularly interested in the ratio of two characteristics' shadow prices:

(6) $$\frac{r_m}{r_{m'}} \;=\; \frac{\partial D_O\left(\mathbf{C}\,,\mathbf{x}\,,\,t\right)/\,\partial C_m}{\partial D_O\left(\mathbf{C}\,,\mathbf{x}\,,\,t\right)/\,\partial C_{m'}} \quad , \quad m \neq m'$$

The elasticity form of shadow price (5),

(7) $$\varepsilon_{D_O\,,C_m} \;=\; \frac{\partial \ln D_O}{\partial \ln C_m} \;=\; \frac{r_m\, C_m}{R\left(\mathbf{r}\,,\mathbf{x}\,,\,t\right)} \;=\; S_m\;,$$

is especially useful, as log-differentiating (7) with respect to *t* gives a measure of technical change bias (Antle and Capalbo, 1998, p.48):

$$B_{mt} \;=\; \frac{\partial \ln S_m}{\partial t} - \left[\sum_j \left(\frac{\partial \ln S_m}{\partial \ln x_j}\right)\left(\frac{\partial \ln R}{\partial \ln x_j}\right)^{-1}\right]\frac{\partial \ln R}{\partial t}. \tag{8}$$

Equation (8) signifies the extent to which, at given characteristics price ratios, technical improvement tilts the innovation possibility frontier, moving the laboratory's discoveries to a new expansion path so that the characteristics' revenue shares are altered (Figure 2).

The first term in (8) is the gross effect, reflecting (a) the revenue-share change plus (b) any movement, associated with nonhomotheticity, along the expansion path. The second term deducts the latter scale effect, leaving the pure revenue-share or bias effect. It is the pure bias that, under the induced innovation hypothesis, is influenced by characteristics' price ratios. If B_{mt} is positive (negative), the IPF tilts toward (away from) characteristic C_m and technical change is C_m - favoring (-disfavoring) (Antle and Capalbo, 1988).

The Lagrangian of the revenue maximization problem can be used to express the scale (second right-hand side) portion of output bias (8) in a way that is computable from a distance rather than revenue function. Noting, in addition to (4), that $S_m \;=\; \partial \ln D / \partial \ln C_m$ (the m^{th} wheat characteristic's revenue share is the derivative of the distance function with respect to the quantity of that characteristic), we can write the scale portion as

$$B^{scale} = \left[\sum_j \left(\frac{\partial^2 \ln D}{\partial \ln C_m \partial \ln x_j}\right)\frac{1}{S_m}\cdot\left(-\frac{\partial \ln D}{\partial \ln x_j}\right)^{-1}\right]\cdot\left(-\frac{\partial \ln D}{\partial t}\right). \tag{9}$$

The derivation of (9) is provided in the Appendix A.

[Figure 2]

4. Wheat Breeding Considerations

The Japanese Government operates six major wheat breeding stations, including one that is local-government owned: Hokkaido, Tohoku, Hokuriku, Kanto, Chugoku, and Kyushu. Released wheat varieties are filed by year of registration, each accompanied with management details, such as nitrogen application methods and rates, used in its experimental trials (Experimental Data for Norin Registration, Ministry of Agriculture, Forestry, and Fisheries). The annually observed characteristics of each new variety; along with the scientific, genetic, and managerial resources annually allocated to its development; the locational and wheat-type varietal class to which it belongs; and the variety's registration and planting date and station constitute our sample data. Descriptive statistics for each variety are given in Table 1. Standard wheat varieties bring higher yields than do hard varieties but tend to have less protein. Larger grain kernels provide a lower protein percentage than do smaller kernels.

4.1. Gene Resources and Breeding Productivity

Breeding research involves a consecutive introduction of new genetic material. An important way, therefore, to shift an innovation possibility frontier is to introduce new genes, in what is sometimes called *recharge* (Evenson, 1998). Effects of genetic resources or diversity on agricultural production, and in particular on yield stability, have been assessed in several studies (Evenson and Gollin, 1997; Smale et al., 1998). Genetic diversity tends to enhance yield mean while stabilizing yield variance. Gene recharge is the key element in this gene diversification process and thus in technological improvement.

Hence, focusing on the gene recharge rate is an important way to represent gene resources in the laboratory.

A number of approaches have been taken to model the impacts of genetic inheritance (Evenson et al., 1998; Smale et al., 1998). Parent wheats vary in their genetic relatedness or similarity, depending greatly 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, consistent with the literature, a one-one relationship between locational and genetic dissimilarity. In particular, two strains genetically close to one another are regarded here as non-identical if developed at different breeding stations.

To estimate genes' effects on wheat breeding research, we constructed a gene recharge rate for each historical variety. We first defined a variety's historical gene exchange area by examining the *coefficient of shared parentage* (CSP) of each variety pair (Table 2).[5] Pedigree data used for the CSP calculations are, for calculation ease, constructed by replacing varieties' names with their breeding stations' names. CSPs based on breeding station identities tend to be higher than those based on varieties' identities. Table 2 shows that Hokkaido varieties share, on average, less than 20% of their parentage with varieties developed at Fuken stations, while Fuken varieties share from 51% to 61% of their parentage with those developed at other Fuken stations. Fuken varieties, that is, have highly similar parentages. On that basis, we specified four gene-exchange classes in Japan: Hokkaido Standard (HS), Hokkaido Hard (HH), Fuken Standard (FS), and Fuken Hard (FH).[6] Genes introduced into each of these classes from one of the other three, or from foreign countries, are considered to contribute to recharge.

The recharge ("*gene*") variable itself is constructed by considering each variety's three preceding generations. An example of a weighting scheme employed in such construction is shown in Figure 3. Weights are doubled as one moves to a younger (thus more proximate) generation. The sum of the weights assigned to the genetic material drawn from *outside* a given variety's gene exchange class constitutes that variety's *recharge* rate. In Figure 3, genes from domestic Variety A and foreign Variety C have been introduced from outside Variety N's exchange class, namely HS. Variety N's recharge rate therefore is the sum of the weights on Varieties A and C: $2/24 + 4/24 = 0.25$. Gene recharge rates thus also range between zero and one. Sample means of Japanese wheat varieties' gene recharge rates are presented in Table 1.

[Figure 3, Table 1, Table 2]

5. Empirical Specification

With these observations in mind, we consider a variety's characteristics **C** in terms of its per-hectare mean yield (*Y*) and protein content (*P*). Human capital vector $\mathbf{K}_{Hum}$ is represented by the number of scientist-years (*S*) that were engaged in research on the i^{th} variety prior to its registration. Genetic information $\mathbf{K}_{Gen}$ is represented by the rate of recharge *G* of novel genetic material and by indicator variables for the four principal varietal classes in Japan: Hokkaido Hard (D_{H_H}), Hokkaido Standard (D_{H_S}), Fuken Hard (D_{F_H}), and Fuken Standard (D_{F_S}). Management vector **M** consists of the per-hectare quantity *N* of nitrogen applied and zero/one variables indicating whether wide or narrow ridging was employed (D_{NR}) or late-season nitrogen added (D_{AN}). Residual shift factor *t* corresponds to the year in which the variety was registered and reflects such breeding technologies as DNA markers not subsumed under human capital vector $\mathbf{K}_{Hum}$ or genetic information $\mathbf{K}_{Gen}$. In Table 1, for example, the oldest registered variety is Norin 104, registered in 1965 and corresponding to $t = 1$.

A translog functional form, desirable not only for its interpretational ease but the generality with which output linear homogeneity can be maintained, is used for the distance function. It is the most common form in empirical work (e.g., Grosskopf et al., 1995; Coelli and Perelman, 1999; Brümmer et al., 2002). For notational simplicity, let $\{ y_{l\,,}\ y_m \}$ represent the vector **C** of output characteristics (Y = yield in kilograms per hectare, P = percent protein content); $\{ z_j ,\ z_k \}$ refer to scientist years (S) allocated to the given variety and to the quantity of nitrogen (N) applied to it in kilograms per hectare; t be the year registered as a Norin variety, and indicator variables D_i , $i = HH , HS , FH , FS$, represent the four varietal classes.[7] We then have the output distance function

$$
\begin{aligned}
\ln D_O \;=\; & \alpha_0 + \sum_{m=1}^{2}\alpha_m \ln y_m + \frac{1}{2}\sum_{l=1}^{2}\sum_{m=1}^{2}\alpha_{lm}\ln y_l \ln y_m + \sum_{k=1}^{2}\beta_k \ln z_k + \delta_R \ln G \\
(10)\qquad & + \frac{1}{2}\sum_{j=1}^{2}\sum_{k=1}^{2}\beta_{jk}\ln z_j \ln z_k + \beta_{NR}D_{NR} + \beta_{AN}D_{AN} + \frac{1}{2}\sum_{m=1}^{2}\sum_{k=1}^{2}\gamma_{mk}\ln y_m \ln z_k \\
& + \sum_{i=1}^{4}\delta_{it}\, t\, D_i + \sum_{i=1}^{4}\sum_{m=1}^{3}\delta_{imt}\ln y_m\, t\, D_i + \frac{1}{2}\sum_{i=1}^{4}\delta_{itt}\, t^2 D_i
\end{aligned}
$$

where $\alpha, \beta, \gamma, \delta$ are estimated parameters. Equation (10) must be linearly homogeneous in outputs, convex in outputs, and monotonic in inputs and outputs. Linear homogeneity in wheat characteristics is imposed by requiring that $\sum_{m=1}^{2}\alpha_m = 1$, $\sum_{m=1}^{2}\alpha_{lm} = \sum_{m=1}^{2}\gamma_{mk} = \sum_{m=1}^{2}\delta_{imt} = 0$, and quadratic symmetry by $\alpha_{lm} = \alpha_{ml}$, $\beta_{jk} = \beta_{kj}$. The distance function is convex in outputs (Färe and Primont, 1995; O'Donnell and Coelli, 2005) if, with present breeding resources, a laboratory can develop convex combinations of current varieties' characteristics. Monotonicity requires that the distance function's derivative with respect to an output [equation (7)] and an input be respectively positive and negative.[8]

Hedonic equation (1) was estimated by ordinary least squares. Annual data from 2000 to 2006 were drawn for it from the Japanese Milling Industry Association's annual *Quality Assessment of Domestic Wheat* and from the Japanese Rice, Wheat, and Barley Improvement Association's annual reports on miller-level wheat prices. Descriptive statistics from the hedonic estimation are presented in Table 3. Sample size was 200.

Annual experimental-trial data for estimating distance function (10) were taken from *Experimental Data for Norin Registration*, summarized in Table 1. Total sample size was 436, the number of observations varying by variety.[9] Of this total, 92 corresponded to Hokkaido Hard varieties, 190 to Hokkaido Standard, 38 to Fuken Hard, and 116 to Fuken Standard. Following Grosskopf et al. (1995), D_0 is set at unity, implying Japanese wheat research laboratories operate on the boundary of their technical opportunities. Restricted OLS is employed to maintain the unity requirement.[10]

[Table 3]

6. Results

Results of the hedonic analysis of Japanese wheat prices are shown in Table 4. The government's restriction on the range of a one-year price change implies that prices are not, in any given year, necessarily at equilibrium, but instead converge only gradually. We therefore estimate two alternative hedonic models. The first employs every sample point, while the second excludes those in which price reached either the upper or lower government-permitted price bound. The first column of Table 4 provides results for all sample points; the second column excludes those in which price reached the upper or lower bound. In both models, all statistically significant parameters take the expected signs. Protein percentage and hardness boost wheat prices, while ash content and color grader value (*clr*) reduce prices. Indeed, the statistically significant parameters are nearly identical in the two models, suggesting the presence of the government's price band does little to alter our estimates of wheat characteristics' virtual prices.

Model (1) estimates in Table 4 indicate that a one-percent wheat protein increase brings a 0.22% price increase, while a one-percent decrease in ash content raises wheat price by 0.42%. Protein's and ash's marginal implicit values, evaluated at sample means, are respectively \$7.70 and \$91.20. This result is similar to Stiegert and Blanc's (1997), who derived marginal implicit protein values of Japanese imported wheat at between \$4.75 and \$5.75.

A marginal implicit value shows the effect on wheat price of a one-unit change in a given quality characteristic. To provide an idea of each characteristic's percentage contribution to wheat price, we decompose the logs of wheat-price ratios into the logs of the characteristics ratios, using Haruyokoi – a Hokkaido hard wheat – as the base variety (B) because its average price, w_B, is the highest in the sample. The decomposition is

$$(11)\quad \begin{aligned} \ln\frac{w_j}{w_B} = {} & \hat{\beta}_1 \ln\frac{pro_j}{pro_B} + \hat{\beta}_2 \ln\frac{ash_j}{ash_B} + \hat{\beta}_3 \ln\frac{clr_j}{clr_B} + \hat{\beta}_4 \ln\frac{aml_j}{aml_B} + \hat{\beta}_5 \ln\frac{wgt_j}{wgt_j} \\ & + \hat{\beta}_6 \left(hard_j - hard_B\right) + e_j - e_B. \end{aligned}$$

where *j* refers to the j^{th} variety. Results in Table 5 show on average that a wheat's hardness provides, at 74%, the greatest percentage contribution to price. At 17%, protein content provides the next-highest mean price contribution. These contributions are robust to the elimination of boundary, that is presumably non-equilibrium, price levels.

[Table 4, Table 5]

6.1. Wheat Breeding Technology

A naïve government breeding establishment would have regarded each year's varietal price change in Figure 1 as a new revelation of protein's and other wheat characteristics' relative values. A more informed establishment would have recognized that price changes are annually constrained and represent adjustments toward long-run preferences that already are in millers' minds. Because the 2000 price reform likely was well anticipated, breeders presumably have, either way, long developed an expectation of continually rising protein value, an expectation intensified by miller lobbying. Have they responded to this expectation by allocating breeding resources in a way favoring the discovery of protein-rich varieties? Substantial investment and between 10 and 15 years of development are required to bring a new wheat strain on the market. If breeding has been price-sensitive, we therefore expect to observe gradually rising protein content and protein shadow prices in recent innovation possibility frontiers.

Our estimate of that family of frontiers, controlling for on-farm management practices, is shown in Table 6. Statistical significance, reflected in Table 6's *t*-values, is high considering the moderate collinearity expected in any quadratic model. Table 7 summarizes the associated regularity tests. Both at the grand sample mean and at variety-class-specific means, the innovation possibility frontiers are monotonic – that is are negatively sloped and shift outward as inputs rise (as in Figure 2). IPFs also are convex at these same means, and percentages of observations deviating from monotonicity and convexity are mostly low.

6.2. Wheat Breeding Innovation

The coefficient of δ_R, showing the negative of the gene recharge rate's proportional impact on the wheat characteristics producible with given non-gene and local-gene research inputs, is -0.029 in Table 6 and statistically significant at the 5% level. Boosting the inventory of foreign and non-local genetic material by one percent has enhanced the protein and per-hectare yield possibilities in wheat strains by 2.9%. Maintaining easy access to external gene sources has been critical to Japanese wheat breeding progress.

Technical change rates computed from equation (4) – and indicated in Table 8 – indicate the negatives of the mean annual proportional expansions in protein and yield possibilities producible with given scientist-year and external-gene resources. That is, they correspond to the Solow-residual notion of technical progress. In the present analysis, they presumably largely reflect qualitative improvements in scientist human capital and expansions in such physical capital as laboratory equipment, neither of which are represented among the equation (10) and Table 6 inputs. As Table 8 shows, characteristics possibilities have expanded more rapidly in Fuken (non-Hokkaido) than in Hokkaido varieties. That is consistent with the availability of old Hokkaido genetic material for Fuken hardwheat breeding purposes, a reciprocal advantage Hokkaido strains do not enjoy from Fuken material. Protein-yield combinations achievable in Fuken Standard varieties with given non-local-gene inputs have expanded an average 2.4% per year, compared with

1.75% per year in Hokkaido Standard varieties. Technical improvement has been nearly the same in Hard as in Standard strains.

Especially important for our purposes are the technical change biases and shadow price ratios implied in the Table 6 regressions. Estimated gross, net, and scale-effect technical change biases [equation (8)], evaluated at each of the four varietal classes' sample means, are given in Table 9. Consistent with the significant rise we have observed in the effective relative value of wheat protein, technical improvement in Japanese wheat breeding laboratories has been protein-favoring and yield-disfavoring. For example, controlling for mean laboratory resources and the characteristics prices themselves, protein's share of virtual breeder revenue has risen an average 3.7% per year among Hokkaido Standard varieties and 3.3% per year among Fuken Standard varieties, moving breeders onto more protein-favoring expansion paths. Mean per-hectare yields in the Hokkaido Standards correspondingly have fallen 6.1% per year, and in the Fuken Standards 5.8% per year. Similar though generally smaller shifts have been present in the Hokkaido Hard varieties. Only in Fuken Hard varieties is a (small) net bias evident toward per-hectare yield and against protein, owing to the excess of the scale effect over the gross effect. Japanese Government wheat breeding laboratories have, despite their not-for-profit status, therefore been responding to expected increases in the relative value of protein by largely allocating scientific resources toward the discovery of protein-rich varieties.

Such argument is reinforced by observing how the shadow prices of protein have changed relative to those of per-hectare yield, since these shadow-price ratios reflect the very IPF slopes that, on the evidence of the Table 9 bias measures, have tilted toward protein. Our earlier discussion of induced innovation theory suggests that observed technical change biases should respond to increases in the relative implicit price of protein. That hypothesis is confirmed in the shadow price ratios (r_Y / r_P) computed from equation (6) and shown in Table 10. These ratios are plotted in Figure 4 by wheat type. Consistent with protein-favoring technological bias, yield-to-protein shadow price ratios have, except in Fuken Hards, trended downward during the 32-year sample period. Fitting a trend to the non-Fuken-Hard shadow price ratios in Table 10 gives $\ln(r_y / r_p) = -1.753 - 0.025t$, with *t*-values -8.26 and -3.22. The significant negative slope indicates a downward trend in the shadow price ratio, that is a relative increase in protein's shadow price. Furthermore, the fact that technical change in Fuken Hard varieties has been slightly protein-disfavoring is consistent with the absence of such a downward trend in its shadow price ratio.[11] In other words, changes in Japanese wheat breeding strategy again appear to have been consistent with market demand changes.

[Figure 4, Table 6, Table 7, Table 8, Table 9, Table 10]

7. Conclusions

Recent Japanese Government policy changes permitting millers to link wheat prices to grain quality are turning wheat breeders' attention to quality characteristics. An output version of induced innovation theory would suggest that breeding successes shift toward the quality characteristics whose relative prices have been permitted to rise. To examine such an hypothesis, we have exploited the fact that an output distance function may be used to represent the wheat characteristics combinations that Japanese breeding programs can achieve with given technical resources. Rates at which wheat characteristics are traded off on the frontier of this set ought, for a revenue-maximizing breeding program, to be equated to the corresponding ratios of the wheat characteristics' actual or implicit market prices. Thus, if observed shadow prices are shifting in the same direction as relative market prices, we will have evidence that breeding programs in Japanese laboratories are responding to market forces, and in a way consistent with maximizing the revenues achievable with a given set of breeding resources.

In order to test whether this has in fact been occurring, it is important to control in an explicit way for the effects of laboratories' gene resources on breeding success. We have done so by employing what we call the 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. That is, external gene pools substantially boost the growth rate of wheat characteristics combinations achievable with a given set of non-gene research resources. 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.

Parametric results drawn from a translog output distance function, and controlling for genetic resources, show that technical change in Japanese breeding has in recent years indeed favored protein over other wheat characteristics. Responding rationally to government price-policy changes, breeders have reallocated scientific resources in a way that shifts wheat characteristics' transformation curves toward grain protein and, proportionally speaking, away from per-hectare yield performance. Although Japanese wheat breeding laboratories operate in the public sector and are thus insulated from profit incentives, their research resource allocations are demonstrably price sensitive.

Japanese wheat markets recently have been even further liberalized. Beginning in 2007, miller-level prices of imported wheat were permitted to fluctuate with international prices, suggesting the implicit price of protein and of other market-desired characteristics will continue to rise. That in turn implies domestic Japanese wheats will confront even greater international competition than in the past, and that pressure for Japanese wheat breeders to develop higher-quality wheat strains will continue to grow.

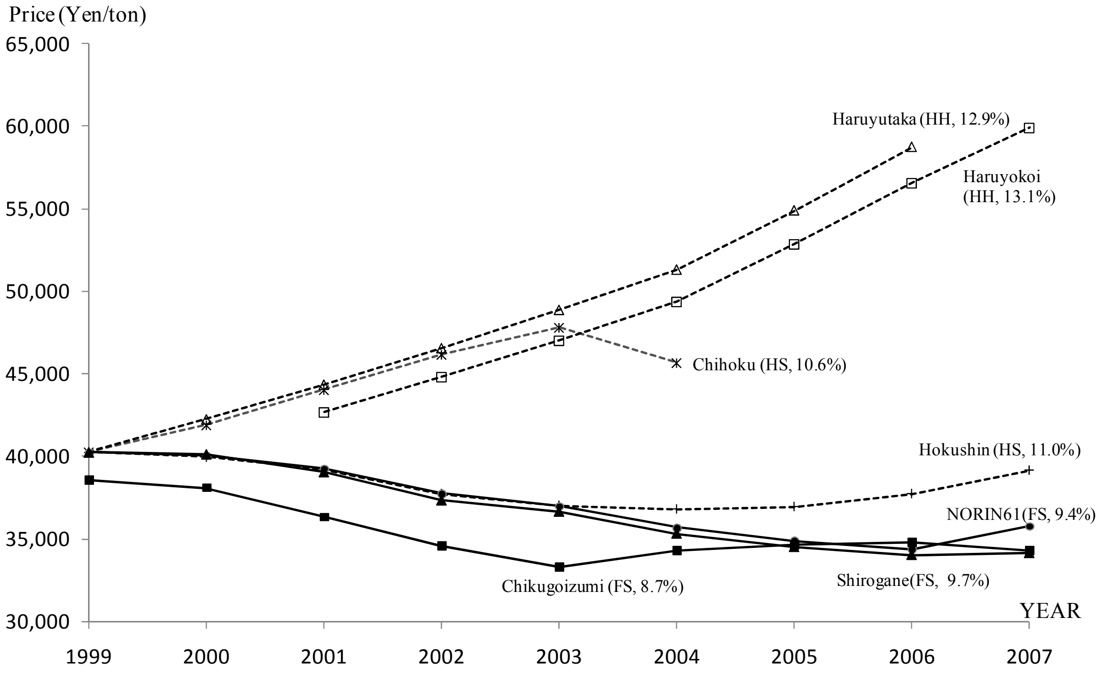

Figure 1. Japanese Miller-Level Wheat Prices, by Varietal Class.

Note: Numbers in parentheses indicate varietal class (HS, HH, FS, and FH) and protein percentage.

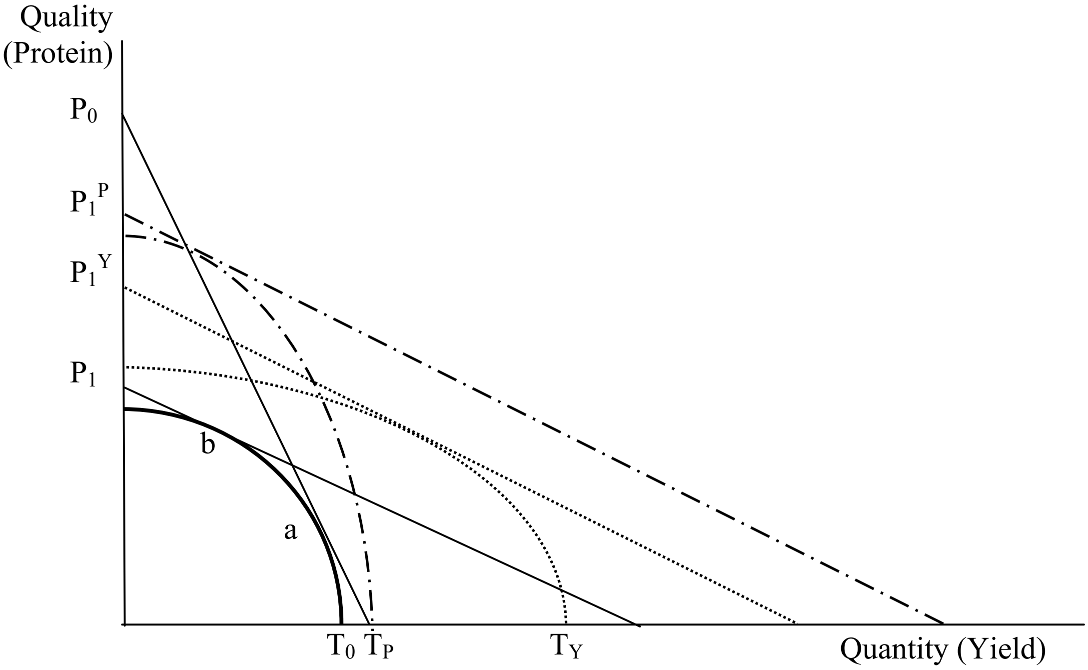

Figure 2. An Innovation Possibility Frontier View of Technical Change in Wheat Breeding Research

Table 1. Means of Wheat Breeding Variables, by Variety

Region	Type	Norin number	Registered Year	t	Variety Name	OBS	Gene Recharge Rate	Nitrogen (kg/ha)	Scientist Years	Yield (kg/ha)	Protein content (%)
Hokkaido	Standard (HS)	108	1968	4	Muka	16	0.62	53.3	35	4,296	9.1
		114	1974	10	Horoshiri	52	0.54	97.5	52	5,743	10.4
		115	1974	10	Takune	19	0.67	98.5	40	5,168	12.1
		126	1981	17	Chihoku	49	0.29	111.8	44	5,828	9.2
		136	1990	26	Taisetsu	12	0.50	122.5	58	7,115	9.8
		142	1995	31	Hokushin	27	0.21	118.1	69	6,125	9.7
		149	2000	36	Kitamoe	15	0.08	112.7	77	5,721	9.7
			Sample Means			190	0.41	103.3	52.1	5,725	9.9
	Hard (HH)	104	1965	1	Haruhikari	17	0.71	74.7	57	3,486	13.2
		130	1985	21	Haruyutaka	35	0.50	109.1	56	4,123	13.1
		139	1993	29	Haruno akebono	30	0.25	118.3	65	4,162	12.1
		150	2000	36	Haruhinode	10	0.25	115.0	72	4,026	12.9
			Sample Means			92	0.43	106.4	60.9	4,008	12.8
Fuken	Standard (FS)	119	1975	11	Toyoho	4	0.83	45.0	113	3,783	8.0
		128	1983	19	Fukuwase	1	0.08	127.0	47	4,460	10.0
		132	1988	24	Aira	14	0.33	54.6	67	5,257	9.3
		133	1988	24	Koyuki	7	0.67	102.0	66	3,980	14.0
		134	1989	25	Daichino minori	4	0.21	119.0	36	4,743	8.3
		135	1990	26	Bandou	16	0.25	51.6	76	5,189	9.7
		137	1992	28	Akitakko	6	0.08	107.0	72	4,200	11.4
		138	1992	28	Abukuma wase	7	0.12	118.2	69	3,619	8.9
		140	1993	29	Kinuiroha	7	0.37	117.1	45	3,874	8.7
		141	1993	29	Chikugoizumi	4	0.08	116.8	23	4,998	7.7
		144	1995	31	Nishihonami	5	0.17	84.4	29	4,348	8.4
		145	1999	35	Iwaino daichi	5	0.08	110.2	41	4,924	8.5
		147	1999	35	Ayahikari	10	0.17	41.4	42	5,882	10.1
		152	2000	36	Nebarigoshi	8	1.00	76.0	48	3,780	11.3
		156	2002	38	Fukusayaka	7	0.46	92.8	47	4,707	8.0
		163	2005	41	Uraramochi	6	0.04	45.0	36	5,893	10.8
		164	2005	41	Fukuhonoka	5	0	98.6	43	5,038	7.7
			Sample Means			116	0.31	79.8	56.0	4738	9.6
	Hard (FH)	146	1999	35	Nishinokaori	5	0.50	111.6	52	3,902	11.0
		153	2001	37	Haruibuki	10	0.67	78.0	47	4,800	14.3
		155	2002	38	Tamaizumi	12	0	40.5	45	4,338	12.8
		157	2002	38	Yukichikara	7	0.12	79.0	106	4,210	13.0
		160	2003	39	Minamino kaori	4	0.54	117.0	53	3,943	10.8
			Sample Means			38	0.32	74.9	58.5	4338	12.8

Note: "Sample means" in the OBS column refer to total numbers of observations in the varietal class.

Source: *Experimental Data for Norin Registration*

Table 2. Means of Wheat Coefficients of Shared Parentage (CSP), Japan

	Fuken				
	Tohoku	Hokuriku	Kanto	Kinki	Kyushu
Hokkaido	0.24	0.20	0.19	0.19	0.20
Tohoku		0.61	0.55	0.53	0.53
Hokuriku			0.61	0.58	0.58
Kanto				0.54	0.53
Kinki					0.51

Note: CSP is computed for each varietal pair, then aggregated by region. See footnote 3.

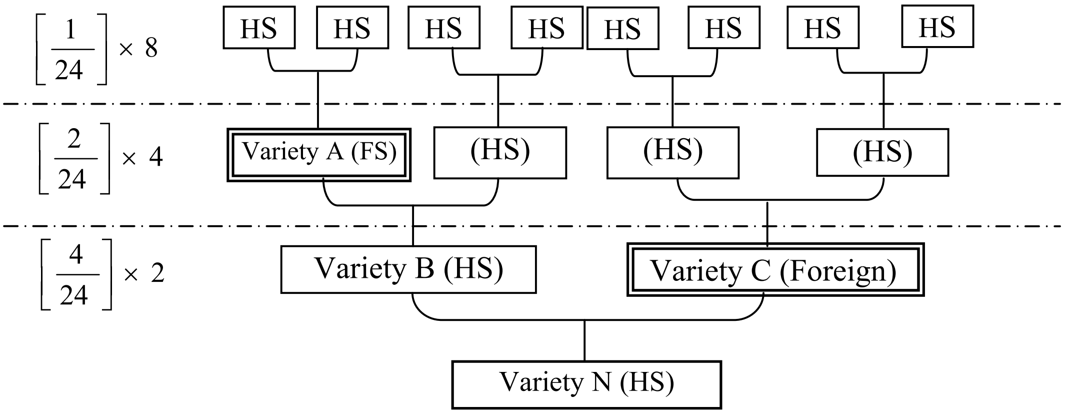

Figure 3. An Approach to Computing a Gene Recharge Rate

Note: Figures at left are weighted contributions summing to unity.

Table 3. Japanese Wheat Price and Quality, Descriptive Statistics

Variable	Mean	St.dev	Min.	Max.
price (yen)	37,390	5,141	29,108	59,919
protein content rate	9.68	1.17	7.90	13.40
ash content	1.55	0.08	1.31	1.79
color (volor grader value)	-1.25	0.68	-3.00	0.50
amylo(B.U.)	885	203	330	1435
weight(kg/l)	809.4	16.4	766.0	854.0

Source: *Quality Assessment of Domestic Wheat* Japanese Milling Industry Association
Annual reports on miller-level wheat prices, Japanese Rice, Wheat, and Barley Improvement Association

Table 4. Hedonic Japanese Wheat Price Regressions, Parameter Estimates

Variable	Model (1)		Model (2)	
	Parameter	t-value	Parameter	t-value
ln*pro*	0.218**	2.53	0.238***	2.8
ln*ash*	-0.415***	-2.94	-0.433***	-3.03
ln*clr*	-0.077**	-2.33	-0.073**	-2.35
ln*aml*	0.022	0.43	0.045	0.94
ln*wgt*	0.684	1.47	0.294	0.62
hard	0.311***	6.91	0.280***	3.73
Year dummy	Yes		Yes	
Boundary prices included	Yes		No	
OBS	200		188	
R^2	0.54		0.43	

Note: **, ***indicate statistical significance at 5% and 1%, respectively.

Table 5. Characteristics Decomposition of Japanese Wheat Prices (percentages)

Variety Name	Price Difference	Protein	Ash	Color	Amylo	Hardness	Weight	Residual
Haruyutaka	-5.4	-4.9	0.6	-7.7	-18.1	0.0	12.0	-81.9
Horoshiri	-18.6	-26.7	11.7	-10.2	-11.2	-167.7	-8.4	112.6
W8	-21.5	-11.5	10.1	3.3	-2.6	0.0	-12.8	-86.6
Chihoku	-22.4	-20.4	22.5	0.4	-4.9	-138.9	-11.9	53.1
Taisetsu	-22.9	-31.1	26.9	1.7	-3.7	-135.9	-7.6	49.7
Kinunonami	-26.7	-36.6	19.1	15.1	2.2	-116.7	-10.5	27.2
Ayahikari	-34.0	-20.5	9.7	-3.5	1.0	-91.6	-4.4	9.3
Tsurupikari	-36.2	-25.1	5.5	3.1	0.8	-86.1	-7.4	9.2
Kitanokaori	-36.4	-2.3	0.9	-5.7	-4.1	0.0	1.7	-90.4
Hokushin	-39.4	-10.3	9.6	-2.8	-0.8	-78.9	-3.1	-13.6
Bandowase	-41.2	-17.5	8.6	-4.8	-2.9	-75.5	-12.5	4.7
Shirogane	-46.1	-11.4	-3.6	-1.6	-0.4	-67.6	-6.8	-8.7
Nambu	-46.4	-15.1	8.4	6.0	-1.1	-67.1	-6.0	-25.0
Norin61	-47.8	-15.7	1.1	-1.5	-0.9	-65.1	-6.7	-11.2
Chikugo	-48.5	-18.2	7.0	-1.6	0.1	-64.1	-6.2	-16.9
Kitamoe	-49.7	-9.3	5.2	0.2	-2.1	-62.6	-1.7	-29.8
Iwainodaichi	-51.3	-18.3	12.7	4.1	0.5	-60.6	-2.9	-35.5
Nebarigoshi	-58.6	-10.8	9.6	-4.6	-0.3	-53.1	-2.4	-38.4
Average	-36.3	-17.0	9.2	-0.6	-2.7	-74.0	-5.4	-9.6

Note: Numbers in columns (3) through (9) sum to -100%.

Table 6. Output Distance Function Parameter Estimates, Japanese Wheat Breeding

Parameter	Estimate	t-ratio	Parameter	Estimate	t-ratio
α_0	0.327	0.23	$\delta_{D_{HS},t}$	0.019 ***	2.59
α_Y	-0.722	-1.72	$\delta_{D_{HS},Y,t}$	-0.011 ***	-2.66
α_P	1.722 ***	4.11	$\delta_{D_{HS},P,t}$	0.011 ***	2.66
β_N	0.439	1.31	$\delta_{D_{HS},t,t}$	0.000	0.04
β_S	-1.055	-1.64	$\delta_{D_{HH},t}$	0.005	0.86
α_{YY}	0.437 ***	6.20	$\delta_{D_{HH},Y,t}$	-0.008 *	-1.91
α_{YP}	-0.437 ***	-6.20	$\delta_{D_{HH},P,t}$	0.008 *	1.91
α_{PP}	0.437 ***	6.20	$\delta_{D_{HH},t,t}$	0.000	1.32
β_{NN}	-0.059	-1.06	$\delta_{D_{FS},t}$	0.002	0.50
β_{NS}	-0.108	-1.40	$\delta_{D_{FS},Y,t}$	-0.005 ***	-2.71
β_{SS}	0.181	1.19	$\delta_{D_{FS},P,t}$	0.005 ***	2.71
γ_{YN}	-0.154	-1.56	$\delta_{D_{FS},t,t}$	0.000	0.72
γ_{PN}	0.154	1.56	$\delta_{D_{FH},t}$	-0.012	-0.60
γ_{YS}	0.271	1.45	$\delta_{D_{FH},Y,t}$	-0.002	-0.75
γ_{PS}	-0.271	-1.45	$\delta_{D_{FH},P,t}$	0.002	0.75
			$\delta_{D_{FH},t,t}$	0.000	0.47
			δ_{D_G}	-0.029 **	-2.01
			$\delta_{D_{AN}}$	-0.060 ***	-2.67
			$\delta_{D_{NR}}$	-0.194 ***	-7.09

OBS = 436

Note:*** , ** , and * indicate statistical significance at 1%, 5% and 10%, respectively.

Table 7. Tests of Properties of Estimated Output Distance Function

		All-Data Mean	Hokkaido		Fuken	
			Standard	Hard	Standard	Hard
Monotonicity	$\partial \ln D_0 / \partial \ln Y$					
	Mean	0.30	0.38	0.16	0.36	0.30
	% negative		0.00	3.26	4.31	5.26
	$\partial \ln D_0 / \partial \ln P$					
	Mean	0.70	0.62	0.84	0.64	0.70
	% negative		0.00	0.00	0.00	0.00
	$\partial \ln D_0 / \partial \ln SY$					
	Mean	-0.11	-0.10	-0.16	-0.09	-0.13
	% positive		2.63	0.00	22.41	5.26
	$\partial \ln D_0 / \partial \ln N$					
	Mean	-0.10	-0.11	-0.09	-0.09	-0.06
	% positive		4.21	3.26	2.59	15.79
	Convexity in outputs	satisfied	satisfied at mean	satisfied at mean	satisfied at mean	satisfied at mean
	% violated		0.00	0.00	0.00	0.00

Table 8. Technological Change Rates in Japanese Wheat Breeding

Location	Wheat type	$\varepsilon_{D_0,t}$
Hokkaido	Standard (H_S)	-0.0175
	Hard (H_H)	-0.0168
Fuken	Standard (F_S)	-0.0240
	Hard (F_H)	-0.0244

Note: Computed from equation (4).

Table 9. Bias of Technological Change in Japanese Wheat Breeding

Location	Wheat type	Yield (*Y*)			Protein Content (*P*)		
		$B_{Y,t}$	$B_{Y,t}^{gross}$	$B_{Y,t}^{scale}$	$B_{P,t}$	$B_{P,t}^{gross}$	$B_{P,t}^{scale}$
Hokkaido	Standard (H_S)	-0.061	-0.030	0.031	0.037	0.018	-0.018
	Hard (H_H)	-0.045	-0.046	-0.001	0.009	0.009	0.0002
Fuken	Standard (F_S)	-0.058	-0.015	0.043	0.033	0.009	-0.024
	Hard (F_H)	0.008	-0.006	-0.015	-0.003	0.003	0.006

Note: Computed from equation (8).

Table 10. Estimated Protein/Yield Shadow Price Ratios

Registered Year	Variety Number and Name	r_Y / r_P	Registered Year	Variety Number and Name	r_Y / r_P
	Hokkaido Standard			Fuken Standard	
1968	108 Muka	0.173	1975	119 Toyoho	0.306
1974	114 Horoshiri	0.148	1983	128 Fukuwase	0.111
1974	115 Takune	0.103	1988	132 Aira	0.183
1981	126 Chihoku	0.102	1988	133 Koyuki	0.068
1990	136 Taisetsu	0.085	1989	134 Daichino minori	0.104
1995	142 Hokushin	0.066	1990	135 Bandou	0.187
2000	149 Kitamoe	0.050	1992	137 Akitakko	0.098
	Hokkaido Hard		1992	138 Abukuma wase	0.072
1965	104 Haruhikari	0.127	1993	140 Kinuiroha	0.081
1985	130 Haruyutaka	0.059	1993	141 Chikugoizumi	0.078
1993	139 Haruno akebono	0.053	1995	144 Nishihonami	0.078
2000	150 Haruhinode	0.025	1999	145 Iwaino daichi	0.091
	Fuken Hard		1999	147 Ayahikari	0.123
1999	146 Nishinokaori	0.116	2000	152 Nebarigoshi	0.048
2001	153 Haruibuki	0.109	2002	156 Fukusayaka	0.099
2002	155 Tamaizumi	0.122	2005	163 Uraramochi	0.093
2002	157 Yukichikara	0.158	2005	164 Fukuhonoka	0.095
2003	160 Minamino kaori	0.117			

Note: Computed from equation (6). Shadow price is evaluated at the mean of the indicated variety number.

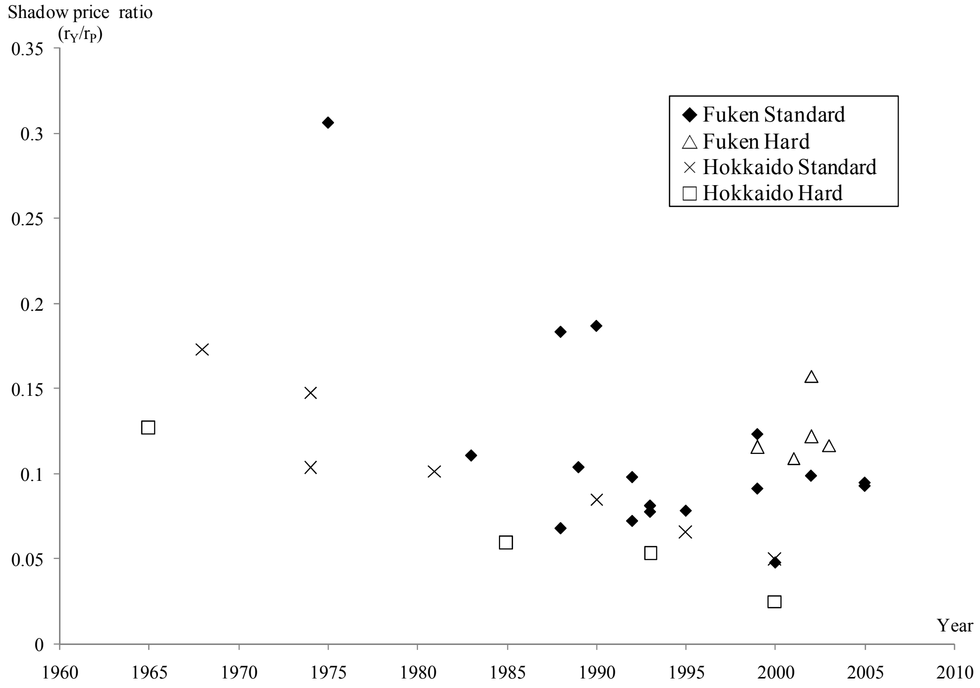

Figure 4. Protein/Yield Shadow Price Ratios, by Wheat Type

Note: Shadow price ratios are given in Table 10.

Appendix A

Given equation (7), $S_m = \partial \ln D / \partial \ln C_m$, the second derivative of the output distance function with respect to input *j* is

(A.1) $$\frac{\partial S_m}{\partial \ln x_j} = \frac{\partial^2 \ln D}{\partial \ln C_m \partial \ln x_j}.$$

Multiplying both sides by $\frac{1}{S_m}$, we have the first term in equation (8):

(A.2) $$\frac{\partial \ln S_m}{\partial \ln x_j} = \frac{\partial^2 \ln D}{\partial \ln C_m \partial \ln x_j}\frac{1}{S_m}$$

Applying the envelope theorem to the Lagrangian of the revenue maximization problem (Färe and Primont, 1995, p.53, equation 3.2.10), we obtain

(A.3) $$\frac{\partial R}{\partial x_j} = -\theta \cdot \frac{\ln D}{\ln x_j}.$$

Noting that $R(\mathbf{r},\mathbf{x}) = \theta(\ \mathbf{r},\mathbf{x}\ )$ (Färe and Primont, 1995, p.54), and multiplying both sides of (A.3) by x_j , gives

(A.4) $$\frac{\partial \ln R}{\partial \ln x_j} = -\frac{\partial \ln D}{\partial \ln x_j}.$$

That is, the derivative of the revenue function with respect to an input is equivalently the derivative of the distance function with respect to that same input. Substituting equations (4), (7), and (A.4) into equation (8) gives equation (9).

Footnotes

[1] Binswanger (1978) expresses this by observing that research resources can be allocated efficiently only if the bias of technological change favors the good with the higher relative price.

[2] Standard and Hard wheats are distinguished by their protein percentages, the former containing less protein. The quality of protein also differs in them.

[3] The role of human capital in productivity growth has been analyzed extensively. Dietz and Bozeman (2005) consider human capital as an input to publication and patent productivity. Their examination of researcher careers shows that career transitions, such as from industry to academia, boost research productivity.

[4] The popularity of distance functions in empirical work likely owes to the fact that convexity and other regularity properties are better understood in distance than in transformation functions.

[5] The CSP – sometimes called a Coefficient of Parentage (COP) – between varieties A and B can be found as $CSP_{AB} = \sum_{j}^{k} (0.5)^{n_{Aj} + n_{Bj}}$, where *j* is the parent variety common to varieties A and B, *k* is the total number of common parents, and *n* is the number of generations to the corresponding common parents. (1 - CSP) is often used as an indicator of biodiversity (Meng, E. C. H, et al., 1998).

[6] Standard wheat and hard wheat are biologically impossible to crossbreed.

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

[8] That is, monotonicity requires $\partial D_0 / \partial P > 0,\ \partial D_0 / \partial Y > 0,\ \partial D_0 / \partial x < 0$.

[9] A given variety's trial data, which begin to be available several years prior to the variety's registration, correspond to alternative fertilizer (nitrogen) applications rates and management practices. In addition to those pre-registration records, annual data often are available for some years after registration, as they are used for comparison to subsequent varieties.

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

[11] A possible reason for Fuken Hard varieties' departure from the generally protein-favoring bias in Japanese wheat breeding is that these varieties have been released only recently, so that laboratories may not yet have discovered a firm breeding objective.

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