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Factors Influencing Wheat Yield and Variability: Evidence from Manitoba, Canada

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Production functions to explain regional wheat yields have not been studied extensively in the Canadian prairies. The objective of this study is to employ a Just-Pope production function to examine the relationship between fertilizer inputs, soil quality, biodiversity indicators, cultivars qualifying for Plant Breeders' Rights (PBR), and climatic conditions on the mean and variance of spring wheat yields. Using regional-level wheat data from Manitoba, Canada, model results show nitrogen fertilizer, temporal diversity, and PBR wheat cultivars are associated with increased yield variance. Mean wheat yield is reduced by the proportion of land in wheat, the interaction of growing temperature and precipitation, and spatial diversity. By contrast, higher soil quality and PBR wheat cultivars increase mean yield. The wheat yield increases attributed to PBR range from 37.2 (1.4%) to 54.5 kg/ha (2.0%). Plant Breeders' Rights may have enhanced royalties from increased certified seed sales, but the benefits in terms of higher wheat yield or lower yield variability are limited. Future research is required to understand the interactive effects of fertilization practices, genetic diversity, and environmental conditions on regional wheat yield stability.

Key Words: climate, fertilizer, Manitoba, Plant Breeders' Rights, production risk, wheat, yield

JEL Classifications: O18, Q16

The wheat economy in Manitoba has undergone structural changes with wheat yields failing to keep pace with other competing crops, such as the oilseed canola (Statistics Canada, 2007). However, understanding of the environmental variables that affect regional wheat yield is limited and estimation of yield functions to identify wheat yield variability have received little attention in Canada. Substantive progress has been made over the years to gain a better understanding of nitrogen effects and application dates on spring wheat yield under field experimental conditions (Holzapfel et al., 2007; Subedi, Ma, and Xue, 2007; Tiessen et al., 2005). However, the manner in which nitrogen fertilizer, cultivar characteristics, and environmental conditions affect regional wheat yields has received little attention, since regional wheat yield and input data are not readily available for the northern Great Plains in Canada. One of the few studies to look at wheat yield response to nitrogen fertilizer in this region found nitrogen to have a

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variance-increasing effect on yield (Smith, McKenzie, and Grant, 2003).

Much of yield increase for spring wheat yield over the last five decades has been attributed to a combination of management, genetic changes, and climatic conditions (McCaig and DePauw, 1995). Wheat advancements have also included improvements in protein levels, days to maturity, straw strength, and maintenance of resistance to major diseases and pests (Graf, 2005). While there are eight registered classes of western Canadian wheat, the Canadian Western Red Spring (CWRS) wheat class, recognized for its breadmaking qualities, represents the largest field crop grown in western Canada, comprising roughly 70% of the prairie wheat area (DePauw, Thomas, and Townley-Smith, 1986). The dominant CWRS wheat cultivar planted in Manitoba is "AC Barrie," accounting for over half of the total Manitoba CWRS wheat area from 1999 to 2002; however, it is now losing its dominance (Canadian Wheat Board, 2007). Wheat growers are adopting newer cultivars with improved traits, and reducing the high concentration of a few cultivars, potentially lowering yield variability, strengthening biodiversity, and avoiding the adverse effects of weather and pest conditions. Wheat producers on the Canadian Prairies tend to select cultivars based more on agronomic considerations (e.g., improvements in yield, days to maturity, and lodging resistance) than on protein content and disease resistance (Walburger, Klein, and Folkins, 1999). Barkley and Porter (1996) found that Kansas wheat producers' cultivar choices are significantly related to production characteristics, such as yield stability, cultivar age, and end-use qualities. In the Canadian system, there exists a tradeoff between production and end-use characteristics that is associated with the class of wheat to be grown and the specific market requirements.

The objectives of this study are to quantify the contribution of fertilizer practices, soil quality, cultivar diversity, cultivars qualifying for Plant Breeders' Rights (PBR), and weather conditions to mean yield and production risk. In this study a Cobb-Douglas production function using a Just-Pope framework is employed to investigate these relationships in Manitoba, Canada. Few studies (Barkley and Nalley, 2007; Roberts et al., 2004; Smale et al., 1998) have investigated wheat yield and production risk as influenced by cultivar diversity characteristics, fertilizer practices, soil quality, and varied weather conditions.

Cultivar Development and Protection

Over the last two decades, new institutional and legal arrangements have been developed to finance wheat research and protect cultivars (Agriculture and Agri-Food Canada, 2004). Publicly funded programs at various government and university institutions have been strengthened by royalty revenues from new cultivars and from producer check-off contributions, administered by the Western Grain Research Foundation. Some private companies, including Agricore United[1] and AgriPro, have established wheat breeding programs in western Canada (Meristem Land and Science, 2006) with privately developed cultivars accounting for roughly 16% of Manitoba CWRS wheat seeded area in 2007 (Canadian Wheat Board, 2007). Since the mid1990s, there has been a shift to industry funding sources for wheat breeding and this has supported the development of over 25 publicly developed wheat cultivars in western Canada (Agriculture and Agri-Food Canada, 2004). Producer participation in the financing of wheat breeding research has expanded the breeding research effort by leveraging complementary research by other research organizations such as the Alberta Agriculture Research Institute (Meristem Land and Science, 2006).

Unlike the United States, Canada has some stringent regulations for the release of wheat cultivars (Dahl, Wilson, and Wesley, 1999). The Canadian Grain Act and Seeds Act are the two statutes that have provided the legal framework for regulating grain quality standards for wheat quality and product uniformity

[1] Viterra was created on September 28, 2007 by the merger of Saskatchewan Wheat Pool and Agricore United.

(Agriculture and Agri-Food Canada, 2005). Before cultivars can be commercially released in Canada, they must be registered by the Canadian Food Inspection Agency. Since 1990 there have been 109 spring wheat and 37 CWRS wheat cultivars registered in Canada (Lindo, 2008). The registration system requires new cultivars to have agronomic characteristics at least equal to or better than a standard cultivar, and meet or exceed quality standards to maintain consistent end-use quality (Dahl and Wilson, 1997). In addition, the Canadian regulatory system requires cultivars of a particular class to be visually distinguishable from registered cultivars of other wheat classes (termed "kernel visual distinguishability" (KVD)).[2] It has been argued that the KVD system has restricted the development of new wheat cultivars (Dahl, Wilson, and Wesley, 1999) and therefore its removal will likely promote the development and registration of cultivars with improved agronomic performance and quality attributes for various end-uses.

In the early 1980s, measures to protect cultivars (e.g., Plant Variety Protection Act (PVPA)) created tremendous debate in the United States as to whether economic incentives would increase private sector investment in research and consequently diminish publicly funded research (Claffey, 1981). Alston and Venner (2002) found the PVPA in the United States has not resulted in any significant increase in commercial or experimental wheat yields and has had little impact on private sector investment in the development of open pollinated wheat varieties. To date, the Canadian Plant Breeders' Rights Act, which was introduced in 1990, has granted protection rights to roughly 58 wheat cultivars (Canadian Food Inspection Agency, 2008). Of these PBR cultivars, 30 are granted to Agriculture and Agri-Food Canada, four to Canadian Universities, five to U.S. universities, and 19 to private seed companies. While the PBR Act has improved access to foreign cultivars (Canadian Food Inspection Agency, 2007), most of the licensed or registered wheat cultivars developed to date have been from publicly and producer financed breeding programs.

In the next section of the paper the analytical framework is described. This is followed by sections that describe the data and estimation methods used, and the results and discussion. The final section of the paper highlights the main findings of the study.

Analytical Framework

Production decisions that growers make regarding input usage and its effect on crop yield and production risk can be modeled by a Just and Pope (1978, 1979) production function. This model includes a response function and a heteroscedastic error term described as follows:

$$Y_{it} = f(X_{it},\beta) + h^{1/2}(Z_{it},\alpha)\varepsilon_{it}, E(\varepsilon_{it}) = 0, Var(\varepsilon_{it}) = 1 \quad (1)$$

where Y_{it} = wheat yield for production region i and year t; X_{it} and Z_{it} are vectors of explanatory variables that need not be identical; β and α are parameters; ε_{it} is a random error vector with mean zero and variance equal to one. The first term in Equation (1), $f(X_{it},\beta)$, represents the mean response function where wheat yield is explained by variables given by X_{it}. The second term, $h(Z_{it},\alpha)$, is the variance function explained by vector Z_{it}. Some input variables can be risk increasing [$\partial h/\partial Z > 0$], while others can be risk decreasing [$\partial h/\partial Z < 0$]. The model is estimated by a three-stage feasible generalized least squares (GLS) procedure described by Judge et al. (1982). First, the regression model of Y_{it} on $f(X_{it}, \beta)$ is estimated by Ordinary Least Squares (OLS). Second, the natural log of the squared residuals of the estimated equation is employed to estimate $h(Z_{it})$, and the yield response is then estimated as a weighted regression of Y_{it} on $f(X_{it}, \beta)$ with weights $h^{1/2}(Z_{it}, \alpha)$. This estimation procedure has been used to evaluate the effects of wheat cultivar diversity and genetic resources on production risks in the Punjab of Pakistan (Smale et al., 1998) and disease and nitrogen risk impacts on winter wheat production in Tennessee (Roberts

[2] As of August 1, 2008 the KVD was removed as a cultivar registration screening criterion for all western Canadian wheat classes (Agriculture and Agri-Food Canada, 2008).

et al., 2004). Other risk studies have used more flexible functional forms than the Cobb-Douglas in estimating mean and variance functions (Asche and Tveterås, 1999).

In this study we analyzed wheat yield and variance response functions for wheat production risk regions of Manitoba, a semiarid region where over a third of the cropped land is generally sown to spring wheat. While there is some empirical work studying the risk effects of nitrogen fertilization on wheat yield variance (Smith, McKenzie, and Grant, 2003), information on the influence of major nutrients such as nitrogen and phosphorus fertilizer, soil quality, cultivars qualifying for Plant Breeders Rights, insurance premium rates, and time trend variables on the mean and variance of yield is limited. Three model specifications are used given a lack of information about fertilizer, soil quality, and technical change effects on mean yield and variability. The mean yield function (Traxler et al., 1995) is described as follows:

$$
\begin{aligned}
Y_{it} = \beta_0 + \sum_{l=1}^{L-1} \alpha_l D_l + B_1 N_{it} + \beta_2 P_{it} \\
+ \beta_3 K_{it} + \beta_4 S_{it} + \beta_5 SQ_{it} + \beta_6 TP_{it} \\
+ \beta_7 GDD_{it} + \beta_8 SD_{it} + \beta_9 VAG_{it} \\
+ \beta_{10} PBR_{it} + \beta_{11} A_{it} + \beta_{12} T + \varepsilon_{it}
\end{aligned} \tag{2}
$$

where Y_{it} is the natural logarithm of CWRS wheat yield (kg/ha) for production region i and time t; the β's and α's are the parameter estimates; D_l is a binary variable to capture heterogeneity in wheat production risk regions; N_{it}, P_{it}, K_{it}, and S_{it} are the natural logarithms of nitrogen, phosphorus, potassium, and sulfur fertilizer rate (kg/ha), respectively; SQ_{it} is a soil quality index; TP_{it} is the natural logarithm of total precipitation (mm); GDD_{it} is the natural logarithm of growing degree days or growing season temperature (°C); SD_{it} is the spatial cultivar diversity index; VAG_{it} is the average cultivar age; PBR_{it} is the percent of CWRS wheat seeded area devoted to cultivars qualifying for Plant Breeders' Rights; A_{it} is the natural logarithm of the percent of annual cropland planted to CWRS wheat, and T (year $2000 = 1$) is time trend variable to capture advances in nongenetic technology.

The yield variance function (Traxler et al., 1995) is given as follows:

$$
\begin{aligned}
\ln e_{it}^2 = \psi_o + \psi_1 N_{it} + \psi_2 P_{it} + \psi_3 K_{it} + \psi_4 S_{it} \\
+ \psi_5 SQ_{it} + \psi_6 TP_{it} + \psi_7 GDD_{it} \\
+ \psi_8 SD_{it} + \psi_9 VAG_{it} + \psi_{10} PBR_{it} \\
+ \psi_{11} A_{it} + \psi_{12} INS_{it} + \psi_{13} T + \mu_{it}
\end{aligned} \tag{3}
$$

where the ψ's are the parameter estimates, INS is the premium rate for multiperil insurance of crop yield, and the other explanatory variables are as defined in Equation (2). Fertilizer (N, P, K, and S) is modeled as a log function for the three variance equations, while $\ln e_{it}^2$ is the natural logarithm of the squared residuals estimated from Equation (2).

Nitrogen fertilizer is expected to have a positive effect on mean wheat yield, especially given the moist conditions for most areas and years in Manitoba, Canada (Manitoba Agriculture, Food and Rural Initiatives, 2006). Nitrogen is the most important fertilizer nutrient for wheat yield and grain protein concentration (Grant, 2006). The impact of nitrogen fertilizer on yield variance could either be positive or negative. Studies in both Canada and Mexico have demonstrated a positive yield variance response to nitrogen fertilizer (Smith, McKenzie, and Grant, 2003; Traxler et al., 1995). In general, one would expect yield variability to be lower in geographic regions where the climate and the soil quality conditions provide consistent or predictable growing conditions. Precipitation during the growing season is expected to have a positive impact on wheat yield while growing degree days could be positive or negative (Hussain and Mudasser, 2007; Hurd, 1994). Increased precipitation and growing degree days have been found to be variance increasing for wheat yield in western Canada (Smith, McKenzie, and Grant, 2003).

The enactment of the PBR Act was designed to give plant breeders the opportunity to develop and protect superior cultivars. Therefore, the infusion of a greater breeding effort by plant breeders would be expected to enhance yield. The impact of PBR on yield variance is unknown. Cultivar biodiversity measures such as temporal and spatial diversity indices are likely to have different effects on mean yield and yield variance since there is very little theoretical evidence predicting the sign of their effects (Smale et al., 1998). In Manitoba, spatial diversity was found to be positively associated with increased canola yields (Carew and Smith, 2006).

There is evidence to suggest that potential wheat yield-explaining variables when employed with aggregated data can provide confusing interpretations due to strong correlations between input variables, which can complicate the findings of empirically derived relationships (Bakker et al., 2005). To address the relationship between wheat yields and economic and climatic variables we estimated three models in order to understand the factors influencing yield variability and reduce the incidence of confounding. Model 1 excluded weather variables but included binary variables for wheat production risk areas. Model 2 included weather variables and binary variables for wheat production risk areas. Model 3 included binary year variables and a trend term to capture improvements in management efficiency. Regional binary variables for wheat growing areas in the models are expected to capture growing conditions that will vary by location in Manitoba. Similarly, binary variables for each year are expected to capture annual changes in growing conditions, such as weather.

Data Descriptions and Sources

Wheat yield, fertilizer, proportion of wheat seeded area, and soil quality data were obtained for 15 crop insurance risk regions of Manitoba (Manitoba Agricultural Service Corporation, 2007). Most of the agricultural soils in Manitoba are black, an indication of high soil organic matter. The remaining areas have gray soils typically developed under forested conditions (Table 1). Wheat cropping is predominantly in the Black soil zone, where the application of relatively high rates of nitrogen combined with adequate moisture contributes to high grain yields. Wheat yield differences from one production region to another may reflect differences in soil quality, input use rates, climatic conditions, and management practices. Some of the CWRS wheat cultivars sown are also likely to differ in protein content. Average wheat yields are generally higher in central and north-western Manitoba than in south-western Manitoba. The latter area is prone to moisture deficits and is deemed to be a higher-risk area.

Annual weather data includes total growing season precipitation (May 1 to July 31) and growing degree days (GDD) (May 1 to August 31). Weather data were collected from principal weather stations corresponding to the wheat production risk regions (Environment Canada, 2007). Some of the wetter regions are in Central Manitoba (Table 1). GDD is calculated as the sum of positive values of the mean [(maximum + minimum)/2] daily air temperatures minus 5°C (Campbell et al., 1997a). There is considerable variability over time in GDD (Table 2). There is also a risk of late spring or early fall frost in the northern regions.

The variance of wheat yield differs across regions because of growing conditions and environmental factors that are difficult to measure and quantify. However, the multiperil crop insurance program in Manitoba introduced in 1960 has a long history of yield and yield variability information that is used to develop crop insurance premium rates. Premiums vary according to the zones of production risk. To account for the determinants of regional wheat yield variability that cannot be accounted for by measurable factors in the model, the crop insurance premium rate for wheat is included as a proxy for inherent yield variability. The insurance premium rate for wheat (based on 70% of the long-term yield), is set by Manitoba Agricultural Service Corporation (Wilcox, 2006).

Several variables required construction. The PBR variable is measured by the percent of CWRS wheat area devoted to PBR cultivars. Wheat cultivars granted PBR are obtained from the Canadian Food Inspection Agency database (Canadian Food Inspection Agency, 2008). The percent of CWRS wheat area devoted to PBR cultivars increased by 4.9% from 2000 to 2006 (Table 2). A weighted soil quality measure was constructed that combines quantitative data of wheat production areas and qualitative variables (soil productivity classes A to J). In

Table 1. Summary Statistics for Canadian Western Red Spring Wheat Growing Areas of Manitoba, 2000–2006

Risk Region	Location	Soil Zone	Soil Quality Index	Cumulative Precipitation (mm)[a]	Cumulative Temperature (°C)[a]	Yield (kg/ha)	Wheat Area (%)[c]	PBR Area (%)[d]	Applied Nitrogen (kg/ha)	Applied Phosphorus (kg/ha)	Applied Potassium (kg/ha)	Applied Sulfur (kg/ha)	Spatial Diversity index	Temporal Diversity (years)
1	South-West	Black	4.17	204.9	2096	2152	23	68.07	61.7	29.2	4.7	2.3	0.32	8.21
2	South-West	Black	5.85	248.3	2016	2600	34	78.70	77.6	32.5	6.8	1.4	0.44	8.37
3	South-West	Black	5.79	234.6	1903	2358	26	67.43	65.3	29.3	6.6	2.5	0.23	7.94
4	Central	Moist Black	6.39	222.5	1903	2619	31	68.36	72.5	29.6	9.3	5.3	0.34	8.32
5	Central	Moist Black	6.75	221.4	1945	2887	33	54.96	80.5	33.4	4.5	3.4	0.30	8.73
10	Central	Moist Black	3.84	244.4	1991	2808	17	86.30	87.2	35.2	16.6	5.5	0.64	8.73
11	Central	Moist Black	6.83	213.0	1981	2950	26	86.42	85.5	37.8	9.8	3.9	0.54	8.24
12	Central	Moist Black	7.04	263.1	2041	3270	6	66.99	85.1	33.6	8.9	3.1	0.43	8.90
32[b]	Central	Moist Black	6.88	259.4	2062	2560	28	89.63	93.9	36.0	3.4	1.8	0.67	8.53
6	North-West	Moist Black	8.16	239.7	1985	2622	33	63.03	78.1	31.3	6.4	4.9	0.23	8.17
7	North-West	Moist Black	8.36	179.9	1790	2673	32	60.01	73.3	33.8	2.3	3.8	0.23	8.63
8	North-West	Moist Black	6.79	247.6	1858	3196	41	34.91	94.3	35.1	15.5	6.1	0.27	8.36
9	North-West	Black-Gray	6.39	159.6	1908	2878	32	52.26	85.0	37.1	17.6	4.8	0.22	8.51
14	East	Gray	6.11	262.3	1888	2490	20	72.72	87.8	32.8	15.4	3.8	0.36	8.63
15	North-Central	Black-Gray	5.11	218.9	1896	2532	19	84.29	83.0	38.9	9.1	2.9	0.50	8.38

[a] Weather stations: Pierson (1), Turtle Mountain (2), Souris (3), Brandon (4), Baldur (5), Neepawa (6), Shoal Lake (7), Mafeking (8), Dauphin (9), Portage Southport (10), Delta Marsh (11), Carman (12), Pinawa (14), Arborg (15), and Emerson (32).

[b] Denotes a risk area comprising of "heavy soils".

[c] Denotes percent of CWRS wheat area of total cropped insured area in Manitoba.

[d] Denotes percent of planted area devoted to cultivars granted Plant Breeders' Rights.

Sources: Manitoba Agricultural Service Corporation (2007); Environment Canada (2007); Canadian Food Inspection Agency (2008).

Table 2. Canadian Western Red Spring Wheat Yields, Cultivars Released, Plant Breeders Rights, Genetic Diversity Indicators, Fertilizer Rates, and Climate Conditions, 2000–2006

Year	Yield (kg/ha)	Cultivars Released[a] (no)	Wheat Area (%)	Plant Breeders' Rights (%)	Temporal Diversity (years)	Spatial Diversity (index)	Applied Nitrogen (kg/ha)	Applied Phosphorus (kg/ha)	Applied Potassium (kg/ha)	Applied Sulfur (kg/ha)	Cumulative Precip.[b] (mm)	Cumulative Temp.[b] (°C)
2000	2846	1	31	65.54	6.40	0.43	79.8	34.5	7.7	3.9	248.1	1902
2001	2213	2	34	67.11	7.06	0.41	78.6	32.8	7.2	3.7	258.8	2056
2002	2539	5	26	67.44	7.82	0.41	80.7	34.5	8.8	3.7	178.0	1930
2003	3171	1	25	68.19	8.43	0.38	81.0	34.5	9.8	3.7	175.8	2129
2004	3145	5	22	72.27	8.87	0.36	82.6	34.2	10.5	3.8	257.0	1609
2005	2087	2	23	71.57	9.93	0.36	82.3	33.6	10.3	3.6	343.6	1927
2006	2944	4	26	70.45	10.60	0.33	79.9	31.9	9.4	3.5	134.4	2130

[a] Pertains to the average number of CWRS wheat cultivars released per year on the prairies.
[b] Pertains to growing season precipitation and temperature (growing degree days).
Sources: Manitoba Agricultural Service Corporation (2007); Canadian Food Inspection Agency (2008); Environment Canada (2007); Lindo (2008).

the 1960s, the Manitoba Crop Insurance Corporation created 10 productivity classes, A to J, based on historical yield data, soil characteristics and climatic factors (Dumanski, Cann, and Wolynetz, 1992). The 'A' soils are considered the most productive in terms of having higher yield potential, while the 'J' soils are least productive due to a variety of factors impeding yield such as excess moisture, drought, high salinity, or poor soil structure. The soil quality index employed in this study is an ordinal measure and is computed by ranking all soil types within a given wheat production area by a rating of 1–10 (e.g., the 'A' soils = 10 and the 'J' soils = 1) and then computing a planted area-weighted average for each wheat production region. A similar measure to proxy soil quality conditions has been used in other empirical studies (Carew and Smith, 2006; Hurd, 1994) to examine the production risk effects associated with canola and cotton yields.

A number of biodiversity indices have been reported in the literature to evaluate their effects on crop productivity (Smale et al., 1998, 2003). In this study two measures of cultivar diversity (spatial and temporal) are employed. Spatial diversity refers to the amount of diversity found in a given geographical area while temporal diversity defines the extent of cultivar turnover or replacement. Spatial diversity is indicated by a Herfindahl index, which is the sum of squared shares of area planted to each variety. A spatial index value close to one indicates that a single variety occupies the bulk of the planted area while a value close to zero suggests that a large number of varieties are each planted to a very small area. The spatial index is higher in Central Manitoba than in the North-West region of the province and has decreased since 1999 when 63.7% of the area planted to CWRS wheat was "AC Barrie" (Table 2). Spatial diversity depends on traits that are profitable to farmers, the available supply of cultivars with those traits, and the physical features of the production environment (Smale et al., 2003).

Temporal diversity, defined as the weighted average age of varieties planted, is an important indicator of the impact of plant breeding programs on crop yield and serves as a measure of potential exposure to disease epidemics associated with the breakdown of disease resistance in crop cultivars (Smale, 2005). Temporal diversity is measured by the difference between the year when the cultivar is planted and the year it is registered. Cultivar age also tends to capture the dynamics of changing product cycles associated with the appropriation strategies of public and private breeding institutions (Rangnekar, 2002). Since the mid1990s, two publicly developed CWRS wheat cultivars, "AC Barrie" and "AC Domain," have dominated the Manitoba wheat landscape. They are noted for their high yield and protein content and good disease resistance. The increased proliferation of protected varieties over time is associated with wheat cultivars with a longer varietal lifespan (Table 2). This implies that the longer life cycle of cultivars observed over the last few years may have lower variability in end-use quality characteristics due to the longer period they are planted (Dahl and Wilson, 1997). In general, one would expect growers to change varieties when cultivars with superior traits are released. Figure 1 shows the historical dominance of wheat varieties released in the early 1990s is now giving way to newer cultivars such as "AC Superb" that are earlier maturing, have improved disease resistance, are higher yielding, and have equal or better end-use quality characteristics than "AC Barrie."

Results and Discussion

The mean production function is first estimated by OLS. We test for heteroskedasticity by employing several tests (Table 3) with a Breusch-Pagan-Godfrey test statistic of 73.2 with 11 degrees of freedom (Prob < 0.001). We reject the hypothesis of homoskedasticity and conclude the existence of output risk for production inputs. Heteroskedasticity is confirmed by the Goldfeld-Quandt test (79.9). Since panel data are employed in this study, we test for year and wheat region-specific effects by employing Wald Chi-Square tests to determine whether the year or regional intercepts are equal to each other. The Wald tests statistic of 23.7 with 14 degrees of freedom (p value of 0.0496) indicates there is heterogeneity in terms of production characteristics among wheat regions in Manitoba (Table 4). The intercepts for yield by

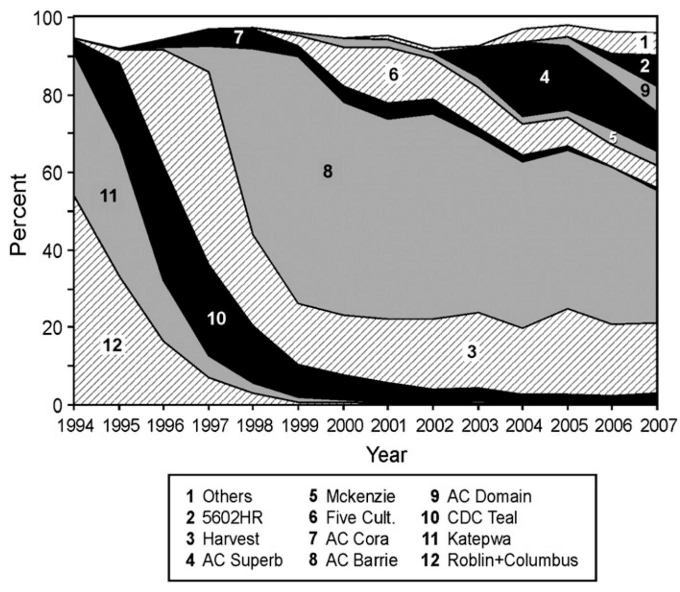

Figure 1. Cultivar Shares of Canada Western Red Spring Wheat Seeded Area in Manitoba, 1994–2007 (Five Cult. included cultivars AC Intrepid, AC Splendor, AC Cadillac, AC Elsa, and Prodigy; others included cultivars CDC Image, CDC Bounty, 5600HR, 5500HR and 5601HR. Source: Canadian Wheat Board (2007))

Table 3. Testing for Heteroskedasticity and Evidence of Production Risk

	χ^2 Statistic	df.	*p* Value
White's Test:			
e^2 on Yhat	2.788	1	0.0950
e^2 on Yhat^2	2.736	1	0.0981
e^2 on Log(yhat^2)	2.838	1	0.0921
Harvey test:	26.411	11	0.0056
Glejser test:	37.589	11	0.0001
Breusch-Pagan-Godfrey:			
Koenker (R^2)	25.753	11	0.0071
B-P-G (SSR)	73.162	11	0.0000
	F-Statistic		
Goldfeld-Quandt:	79.91		

region are not constant and therefore regional binary variables are capturing differences in growing conditions across wheat districts.

Given that yield variance is not constant, the mean response and variance functions are estimated for the J-P model using three model specifications (Tables 5 and 6). The adjusted R^2 values for the mean production function indicate the weighted data fit the models very well. The signs and significance of the independent variables differed between model specifications (Table 5).

An incremental proportion of land planted to wheat decreased wheat yield (Table 5), implying decreasing returns to scale with respect to land (Yang, Koo, and Wilson, 1992). Soil quality differences, as measured by an index, showed soils classified as higher quality as having a positive impact on mean wheat yield (model 2). Studies of cotton in California found a positive yield association with soil quality conditions (Hurd, 1994).

Nitrogen fertilizer is found to be positively associated with wheat yield in model 3. However, two of the models estimated a negative yield response. The aggregated fertilizer rates should reflect optimal input use; therefore, the estimated yield response could be sensitive to the model specification. If producers are applying optimal fertilizer, the incremental yield response to fertilizer could be expected to be small. For model 2, the large negative estimate cannot be explained. It would appear there is some nitrogen interaction with weather or soil quality. Nitrogen is the most expensive nutrient and is used in high amounts to optimize grain yield under wetter climatic conditions (Malhi et al., 2001). The positive response of nitrogen observed in model 3 is consistent with wheat producers' management decisions to optimize their grain yield and protein content (Campbell et al., 1997b). High-yielding wheat requires more nitrogen to support grain and protein yield.

Phosphorus rate did not significantly affect wheat yield. Phosphorus is normally required during the early stages of growth to optimize crop establishment and grain yield. The yield response effects of phosphorus will vary depending on the spring growing conditions, available soil P, and the previous history of phosphorus applications (Grant et al., 2001). Potassium has a negative impact on wheat yields in model 3, but potassium deficiencies for wheat production in western Canadian soils are rare (Stewart and Karamanos, 1986). Sulfur fertilizer has a positive and significant effect only in model 2. Sulfur requirement is closely associated with the amounts of nitrogen applied since sulfur is a building block for proteins and enzymes. The S-containing amino acids are important in forming the high-quality glutenins and gliadins that affect milling and baking quality of wheat (Alberta Agriculture, Food and Rural Development, 2006). However, prairie soils normally contain sufficient sulfur to optimize wheat production.

At the means, the marginal product of precipitation and growing temperature are negative (model 2). The negative interaction of precipitation and growing temperature terms exceeded

Table 4. Tests for the Equality of Region or Year Intercepts for Wheat Risk Regions

	χ^2 Statistic	df	*p* Value
Region			
Wald chi-square test	23.72	14	0.0496
F-statistic	1.69	14 and 79	0.0735
Year			
Wald chi-square test	86.55	6	0.0000
F-statistic	14.42	6 and 89	0.0000

Table 5. Just-Pope Mean Yield Parameter Estimates for Canada Western Red Spring Wheat Production Risk Areas in Manitoba, 2000–2006

Variable	Model 1	Model 2	Model 3
Constant	9.614* (3.83)[a]	−35.967*** (−1.86)	5.230* (6.77)
Proportion of planted wheat area (A)	−0.348** (−2.28)	−0.299*** (−1.82)	−0.090* (−2.56)
Soil quality index (SQ)	—	3.147*** (1.89)	—
Nitrogen fertilizer (N)	−0.624 (−1.12)	−1.786* (−3.03)	0.478** (2.11)
Phosphorus fertilizer (P)	0.221 (0.51)	0.342 (0.71)	0.267 (1.23)
Potassium fertilizer (K)	0.085 (0.80)	0.025 (0.26)	−0.065** (−2.22)
Sulfur fertilizer (S)	−0.037 (−0.34)	0.229** (2.02)	0.035 (0.87)
Precipitation (TP)	—	8.678** (2.49)	—
Temperature (GDD)	—	6.042** (2.46)	—
Precipitation*temperature	—	−1.174* (−2.56)	—
Spatial diversity (SD)	−0.534 (−1.28)	−0.924*** (−1.86)	0.166 (0.71)
Temporal diversity (VAG)	−0.038*** (−1.81)	−0.051** (−2.39)	−0.024 (−0.48)
Plant Breeders' Rights	0.004*** (1.67)	0.006** (1.97)	−0.003*** (−1.76)
Time trend	—	—	−0.395*** (−1.69)
Dummy (risk area 1)	−0.531 (−1.61)	0.340 (0.42)	—
Dummy (risk area 2)	−0.119 (−0.48)	0.114 (0.35)	—
Dummy (risk area 3)	−0.399 (−1.18)	−0.621 (−1.64)	—
Dummy (risk area 4)	−0.166 (−0.50)	−0.642** (−2.13)	—
Dummy (risk area 5)	0.096 (0.34)	−0.346 (−1.33)	—
Dummy (risk area 6)	−0.078 (−0.24)	−1.279* (−2.75)	—
Dummy (risk area 7)	−0.016 (−0.05)	−1.439* (−2.89)	—
Dummy (risk area 8)	0.303 (0.84)	−0.067 (−0.20)	—
Dummy (risk area 9)	−0.091 (−0.26)	−0.338 (−0.97)	—
Dummy (risk area 10)	−0.244 (−0.88)	1.325 (1.37)	—
Dummy (risk area 11)	−0.015 (−0.07)	−0.409** (−1.95)	—
Dummy (risk area 12)	−0.412 (−1.26)	−0.671** (−2.08)	—
Dummy (risk area 13)	−0.331 (−1.18)	−0.304 (−1.01)	—
Dummy (risk area 14)	−0.359 (−1.48)	0.225 (0.45)	—
Dummy (2001)	—	—	−0.144* (−2.55)
Dummy (2002)	—	—	−0.039 (−0.45)
Dummy (2003)	—	—	0.204*** (1.69)
Dummy (2004)	—	—	0.293*** (1.85)
Dummy (2005)	—	—	0.012 (0.06)
Dummy (2006)	—	—	0.420 (1.62)
Adjusted R^2	0.99	0.99	0.99
DW-Statistic	1.79	1.69	1.57
Akaike Information Criterion	4.76	5.85	3.95
Number of Observations		105	

[a] Values in parenthesis are t-values.

*, **, *** significant at 0.01, 0.05, and 0.10, respectively.

the linear term for all but very low precipitation or growing temperature. The growing temperature result is consistent with climate warming predictions that increased evapotranspiration will lead to a reduction in the average spring wheat yield (Raddatz and Shaykewich, 1998). However, Hurd (1994) found heat units, or degree days, had a positive but insignificant effect on cotton yield in California. Wet and cool spring conditions could depress yield because of delayed planting or retarded plant development. In 2005, Manitoba wheat yields were lower than in other years and much of this yield reduction is attributed to excessive early spring moisture

Table 6. Just-Pope Variance Function Estimates for Canada Western Red Spring Wheat Production Risk Areas in Manitoba, 2000–2006

Variables	Model 1	Model 2	Model 3
Constant	−36.471* (−3.25)[a]	−37.753 (−1.62)	−20.310* (−2.65)
Proportion of planted wheat area (A)	−0.649 (−1.43)	0.697 (1.31)	0.016 (0.04)
Soil quality (SQ)	−1.348 (−0.87)	—	−2.106*** (−1.73)
Nitrogen fertilizer (N)	7.328** (1.95)	2.194 (0.73)	5.919** (2.23)
Phosphorus fertilizer (P)	−1.046 (−0.35)	2.948 (0.82)	−1.789 (−0.64)
Potassium fertilizer (K)	−0.817 (−1.56)	0.492 (1.07)	−0.769*** (−1.66)
Sulfur fertilizer (S)	−0.142 (−0.25)	−1.132*** (−1.73)	0.145 (0.28)
Precipitation (TP)	—	0.733 (1.13)	—
Temperature (GDD)	—	0.932 (0.37)	—
Spatial diversity (SD)	−2.354 (−0.76)	—	—
Temporal diversity (VAG)	0.409** (2.37)	0.078 (0.427)	−0.103 (−0.20)
Plant Breeders' Rights (PBR)	0.058* (2.58)	0.002 (0.10)	0.010 (0.66)
Insurance rate (INS)	—	0.290* (1.69)	—
Time trend (T)	—	—	0.251 (0.68)
Adjusted R^2	0.34	0.15	0.13
DW-Statistic	1.64	1.51	1.61

[a] Values in parenthesis are t-values.
*, **, *** significant at 0.01, 0.05, and 0.10, respectively.

resulting in roughly 15% of arable land not being seeded.

The effect of spatial diversity indicates that more wheat area planted to fewer varieties lowered wheat yield (model 2). This result disagrees with a previous study for irrigated wheat districts in the Punjab region of Pakistan (Smale et al., 1998). Alternative modeling approaches found crop genetic diversity can have beneficial effects on farm productivity and managing environment risk for durum wheat farms in Italy (Di Falco and Chavas, 2006). Our study illustrates that the trend toward greater spatial cultivar diversity among Manitoba wheat producers may be lowering their wheat yield. Producers may be diversifying cultivars as a yield maximizing strategy, but not to increase diversity. Cultivars might increasingly have climatic or market niches that result in producers growing a wide spectrum of cultivars.

Temporal diversity, as measured by the average age of varieties grown, has a negative impact on wheat yield. All three models (1, 2, and 3) estimated similar impacts, though not significantly for model 3. The negative impact is consistent with the result found by Smale et al. (1998) for irrigated wheat. Manitoba wheat producers staying with older cultivars are losing the opportunity to increase their yield.

From models 1 and 2 we show the impact of PBR to be positive, while for model 3 it has a negative yield impact. The yield elasticity estimates, at the means, for the three models are 0.28, 0.41, and −0.21, respectively. The yield impacts attributed to PBR range from a decrease of 27.89 kg/ha (1.0%) to a 54.5 kg/ha (2.0%) increase, depending on model specification. Wheat yield increases due to PBR are small at best. The bulk of wheat cultivars granted PBR are publicly developed cultivars licensed and commercialized beginning from the mid1990s. This also corresponded to the period of increased industry funding from the Western Grains Research Foundation research check-off scheme (Graf, 2006). While the legal protection provided under the Canadian PBR Act has enhanced royalties and strengthened wheat yields, there is little evidence that it has expanded the wheat breeding effort in Canada. Supporting data from the Canadian Agricultural Research Council indicated that Professional Scientist Years (PSY) devoted to total wheat research (breeding, disease, agronomy) in Canada have declined by 63% from 111 in 1990 to 41 PSY by 2005 (Willis, 2008). In the

United States, the PVPA may have stimulated public investment in wheat cultivar improvement (Alston and Venner, 2002; Pray and Knudson, 1994). Recent U.S. studies have shown that the PVPA has contributed to the genetic improvement of soft white winter wheat in the State of Washington (Kolady and Lesser, 2009) and cotton yield enhancements (Naseem, Oehmke, and Schimmelpfennig, 2005).

Few of the model variables have a significant impact on wheat yield risk (Table 6). The proportion of planted wheat area had a negligible effect on yield variability. Nitrogen fertilizer had a risk-increasing effect for two of the three models. Increasing yield variance with nitrogen fertilizer is consistent with Smith, McKenzie, and Grant (2003). When growing conditions are favorable, there will be a larger yield response to nitrogen. However when the variability of precipitation and growing heat are taken into account, nitrogen has less of an impact on yield variability. Sulfur (model 2) and potassium (model 3) have a significant risk-reducing effect, but the use of these fertilizers is low and will have minimal impact on yield variability. Wheat growers' inability to predict favorable weather conditions coupled with their decision to target grain yield may explain why nitrogen fertilizer is associated with increasing yield variability.

Spatial diversity had no impact on yield variance (model 1), which is consistent with the findings of Smale et al. (1998). Crop biodiversity measures have been shown to lower the variability of wheat yields only in circumstances of low pesticide usage (Di Falco and Chavas, 2006). Higher average cultivar age is associated with increased yield variability only for model 1.

Wheat cultivars qualifying for PBR had no effect on production risk for models 2 and 3, but is variance increasing for model 1. There is the potential that the newer cultivars are trading off some yield stability to obtain higher potential yield and protein. Public wheat cultivars developed in Kansas increase yield variance relative to cultivars released by private wheat breeders (Barkley and Nalley, 2007). It is not evident from the Barkley and Nalley (2007) study whether these cultivars are protected by PVPA. Higher yield risk in regions with higher crop insurance premium rates, an indicator of increased inherent yield risk, are consistent with an earlier study for canola (Carew and Smith, 2006). Regions in Manitoba, such as the southwest, that have higher premiums also have greater inherent yield variability due to adverse weather conditions such as drought.

Conclusions

We employ a Just-Pope production function to quantify the contribution of nitrogen fertilizer, environmental conditions, cultivar diversity, and cultivars qualifying for PBR on mean yield and variance. Different model specifications were estimated to reduce the incidence of confounding variables. The results need to be viewed within the context of the estimated models and the variables included. We conclude that spatial and temporal diversity has a negative effect on mean yield. Regional wheat yield is lower when a higher proportion of planted land is devoted to wheat. Fertilizer typically increases wheat yield, but with regional data and producers' applying fertilizer at optimal rates, only a small yield response or inconclusive impact is evident. Cultivars protected by PBR have a small positive impact on yield in two of the three models. Wheat yield variance is higher with increased temporal diversity and with greater use of PBR cultivars. Higher quality soils are found to have less yield variability, while nitrogen fertilizer increases yield variability. There is some indication that other fertilizers, such as sulfur, either have a limited yield impact or contribute to less yield risk.

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