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Spillovers and Crowding Effects in a Mixed Biotech Industry: The Case of Canola

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This paper develops empirical models to estimate both interfirm research spillovers and crowding effects in the canola crop research industry. The potential sources of spillover include basic research, human capital/knowledge (as measured through other-firm expenditures), and genetics (as measured through yields of other firms). The model used to examine spillover effects on research productivity provides evidence that there are many positive interfirm nonpecuniary research spillovers, which is consistent with a research clustering effect. The second model, which uses additional data on firm revenue to estimate crowding effects, shows that although private firms tend to crowd one another, public-firm expenditure on basic and applied research creates a "crowding-in" effect for private firms. This model also shows that enhanced intellectual property rights have increased the revenues of private firms.

Key words: applied research, basic research, biotechnology, canola industry, crowding, IPRs, private research expenditures, public research expenditures, research spillovers.

Introduction

Knowledge spillovers have played a prominent role in the development of crop research activity in Canada and the United States. Until recently, the ability of farmers to retain seeds meant that crop breeders were unable to capture the value of their innovations, which limited most of the crop research to public institutions (Huffman & Evenson, 1993).[1] In the past two decades, the ability of modern biotechnology to identify DNA, combined with regulatory and judicial moves to enhance intellectual property rights (IPRs), have limited crop research spillovers. This has resulted in the rapid development of a larger crop research industry dominated by a few private research firms with the continuing presence of public institutions (Fernandez-Cornejo, 2004).

Knowledge spillovers are an important focus of study for economists and policy makers.[2] It is now generally recognized that externalities that arise from the public-good aspects of knowledge are an important determinant of the growth in economic productivity (e.g., Adams, 1990; Griliches, 1992; Jaffe, 1986). The nonrival nature of research output has assumed a central role in endogenous growth theory, both in terms of physical capital (e.g., Aghion & Howitt, 1992; Romer, 1986, 1990) and human capital (e.g., Lucas, 1988).[3] Spillovers also have important implications for firm behaviour (e.g., Adams, 2000; Cohen & Levinthal, 1989; Just & Hueth, 1993; Moschini & Lapan, 1997) and industrial organization and structure (e.g., Dasgupta & Stiglitz, 1980; Fulton, 1997; Fulton & Giannakas, 2001; Lesser, 1998; Levin & Reiss, 1984, 1988; Schimmelpfennig, Pray, & Brennan, 2004; Spence, 1984). This literature highlights the importance of understanding knowledge spillovers within an economy.

A related body of economic research examines the crowding effects of public research investment on private research investment. Roberts (1984), Bergstrom, Blume, Varian (1986), and David and Hall (2000) argue that publicly funded research competes for scarce resources and therefore could "crowd out" privately funded research. Other economists who have considered charitable donations (e.g., Khanna, Posnett, & Sandler, 1995; Khanna & Sandler, 1996) show that public expenditure could have the opposite effect and cause a

1. *The exception was the corn industry, where hybrid technologies eliminated the ability of farmers to retain viable seeds.*
2. *Several studies have specifically dealt with agricultural productivity spillovers (e.g., Alston, Craig, & Pardey, 1998; Evenson, 1989; Griliches, 1979, 1980; Huffman & Evenson, 1993; Johnson & Evenson, 1999; White, He, & Fletcher, 2003), and cross-state spillovers from agricultural research (e.g., Alston & Pardey, 1996; Evenson, 1989; Yee & Huffman, 2001).*
3. *A number of studies have recognized that knowledge is embodied in human capital and that spillovers occur with the education of workers (e.g., Lucas, 1993; Schultz, 1975), learning from others (Foster & Rosenzweig, 1995; Thorton & Thompson, 2001), and with the mobility of workers (Glaeser, Kallal, Sheinkman, & Scheifer, 1992).*

"crowding in" of private research expenditure.[4] Evenson and Kislev (1976) introduced the notion that basic research spillovers may differ from applied research spillovers; this idea was used in a number of later studies (e.g., Kortum, 1997; Lee, 1982, 1985). Diamond (1999) and Robson (1993) empirically examined the crowding effects of basic research.

In this study, we take advantage of a unique data set to empirically examine research spillovers in a modern biotech crop research industry. We use firm-specific and public data in the Canadian canola industry to examine empirically the nature and magnitude of interfirm and public-private spillovers. The potential sources of (nonpecuniary) spillovers examined include basic research (as measured through expenditures), human capital and knowledge (as measured through other-firm applied research expenditures), and genetic spillovers (as measured through variety yields of other firms). Separate models are used to estimate the nonpecuniary spillovers and the crowding effects of rival's research.[5]

The systematic empirical approach of this study is novel in several respects. First, the paper deals with a modern crop research industry where the majority of research is undertaken by private firms. Second, the data is firm specific, which allows an estimation of effects at a firm level. Third, the industry is made up of a mixture of private firms and two forms of public institution, which each are differentiated in the estimation. Fourth, the model separates the spillovers generated from basic and applied research. Finally, the study explicitly examines both nonpecuniary spillovers and crowding effects. Taken as a whole, this study provides a far more comprehensive and disaggregated examination of research spillovers than found in the current literature.

The empirical analysis described in this paper reveals that interfirm and public-private research spillovers in this modern crop research industry are both prevalent and large. Moreover, although private firms tend to crowd each other in the industry, public basic and applied research tends to increase firm revenue consistent with a "crowding-in" effect. The existence of the large spillovers suggest that private incentives and social outcome may diverge, suggesting a need to understand these relationships from a public policy perspective.

Theoretical Framework

Although there is a vast and complex literature that deals with mechanisms for research spillovers and the incentives they create, the measurement of nonpecuniary spillovers on productivity is a more straightforward question: Either the actions of other firms affect a firm's productivity or they do not. We use a simple model to focus on the latter. In the short run, we assume that each breeding firm has some stock of capital and must make decisions about how much to invest in applied research. Each firm will try to maximize their planned level of output for any given amount they invest, resulting in positive relationship between cost and output (Figure 1). The productivity function, or the quantity of output that can be achieved for any given cost, is the inverse of the cost function with respect to output, or

$$Q_i = F(C_i, K_i, O_{j \neq i}), \qquad (1)$$

where Q_i is the level of output, which is a function of firm i's real expenditure, C_i, the capital stock of the firm, K_i, and the activities and assets of other firms, $O_{j \neq i}$. Positive (negative) spillovers increase (reduce) production for any given cost and thus have positive (negative) derivatives in the productivity function. In Figure 1, positive spillovers are reflected as a horizontal rightward shift in the productivity curve. The vertical displacement of the productivity curve in the figure is equal to the change in cost of producing a given level of output due to the spillover.[6]

The second model (Model 2) is developed specifically to examine crowding effects, recognizing that although firms can receive benefits from nonpecuniary spillovers, they also compete for business.[7] To measure crowding effects, we use a revenue function that represents the maximum amount of revenue that can be generated for firm i (R_i), or

4. *David, Hall, and Toole (1999) provided a recent survey of the available empirical evidence and found that the results were inconclusive in terms of the direction and the magnitude of the relationship between public and private research expenditure.*

5. *Nonpecuniary spillovers are the nonmarket impacts of a firm's actions on other firms. Pecuniary spillovers are the firm-to-firm interactions that occur through the market. The combined effects of pecuniary and nonpecuniary spillover measures the net effect of a firm's actions on its rivals or the crowding effect.*

6. *The inverse of the productivity function is the more familiar cost function, $C_{it} = F^{-1}(Q_{it}|K_{it-1}, O_{jt})$. For derivative-order changes, there is direct correspondence between increases in productivity and cost reduction: $dQ_{it} = -(\partial C_{it}/\partial Q_{it})dC_{it}$.*

7. *The intrafirm impacts that take place through the market are referred to as pecuniary spillovers.*

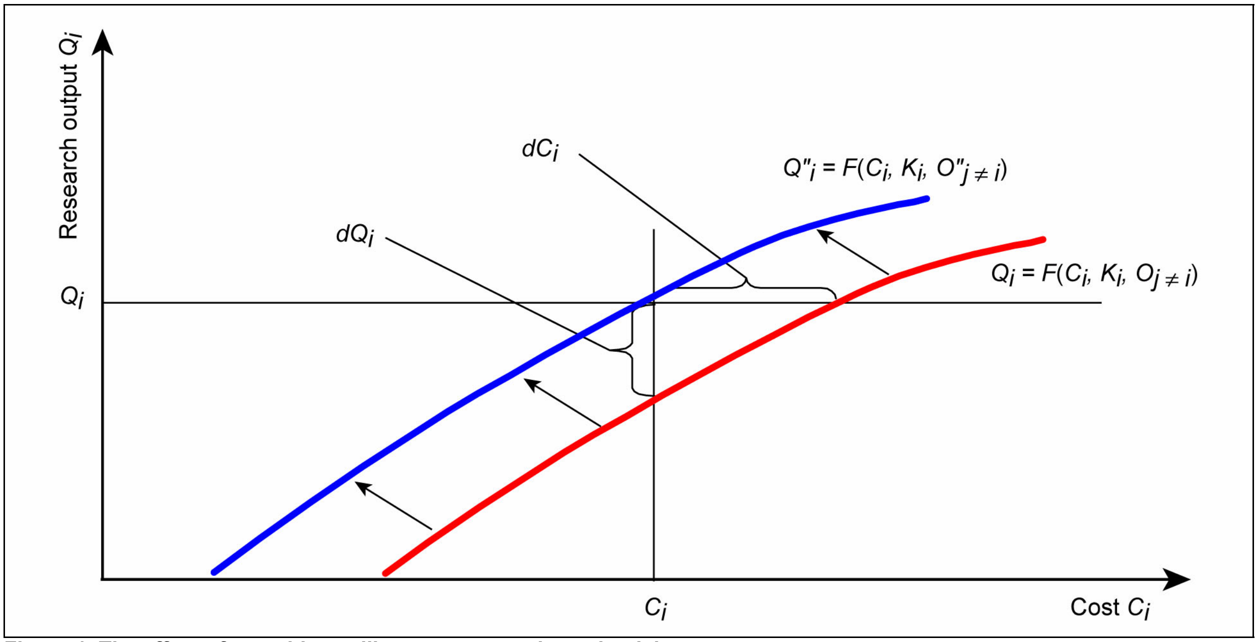

Figure 1. The effect of a positive spillover on research productivity.

$$R_i = R(C_i, K_i, O_{j \neq i}, IPRs), \quad (2)$$

that is a function of its own expenditures, C_i, its capital stock, K_i, the activities and assets of other firms, $O_{j \neq i}$, and the intellectual property rights, *IPRs*. In a profit-maximizing firm, revenue will be an increasing function of its own expenditures and capital stock. If the derivative of revenue with respect to the activities and assets of other firms is positive, then the benefit of (nonpecuniary) research spillovers exceed the negative (pecuniary) competitive effects, and these activities will increase profitability and cause a crowding in of research activity. If, on the other hand, the negative competitive effect of the other firms exceed the positive research spillovers, then these activities will tend to crowd out other research activity. An increase in intellectual property rights would normally have a positive effect on demand faced by research firms, as *ceteris paribus* they would have greater ability to charge for their research output.

The Empirical Model and Estimates

The Canola Industry

Change has been particularly evident in the canola research industry.[8] After three decades of public leadership, the canola industry has become dominated by large private firms employing biotechnology to produce tailored products for the marketplace. In 1970, 83% of the total \$18 million spending on canola research was public investment, while 17% was private; as a result, virtually all varieties were in the public domain. By 1999, the private sector's share had grown to 70% of the total \$149 million research expenditure, which yielded control of approximately 85% of the resulting varieties and more than 90% of the new technologies (Canadian Food Inspection Agency [CFIA], 1998; Canola Research Survey, 1999).

Agricultural producers are now required to sign agreements to use particular technologies and cannot retain seed for subsequent crop production. Many genetic products are also tied to the use of specific inputs (e.g., herbicides) or into particular processing markets. By 2000, at least 75% of canola acreage was subject to some form of annual contracts, as canola acreage was seeded either to herbicide-tolerant (HT) or to hybrid varieties (Malla, Gray, & Phillips, 2004). Finally, the introduction of biotechnology and improved IPRs combined with freedom-to-operate concerns have resulted in a concentrated private canola industry. For example, in 1999, only three private firms (Monsanto, AgrEvo, and Cyanamid) controlled the HT market (Fulton & Giannakas, 2000).

In today's canola industry, both public and private research firms expend resources to develop canola varieties. Private firms engage in applied research to pro-

8. *For more details, see Phillips and Khachatourians (2001).*

duce enhanced crop varieties, which are sold to farmers. Public institutions (firms) also engage in a significant amount of basic research, which creates knowledge that is used to improve crop research processes. The varieties created by public firms are distributed through the private seed industry in return for royalty payments.

Data and Econometric Model Specification

The data used for the econometric analysis came from many industry and government sources and in some cases took considerable calculation to construct each of the variables used for the econometric analysis. We were able to construct a data set for five private firms and two public institutions from 1960 to 2001. The primary data source for research expenditures was a survey of the canola industry (Canola Research Survey, 1999).[9]

We used two different models for the empirical analysis of research spillovers. Model 1 (Equations 3 and 4) corresponds to Equation 1, which is the theoretically specified inverse cost function to measure nonpecuniary spillovers on productivity. In the empirical equations (3 and 4), we use yield of the seed produced as a proxy for research output. Similarly, Model 2 (Equations 5 and 6) corresponds to Equation 2, the revenue function to determine crowding effects. Lastly, to separate research spillovers effects in public firms and private firms, we divided the firms into two groups: private firms and public firms.

9. *A detailed description of the data sources and the calculations used to construct the variables is available from the authors. Research expenditure on canola: Canola Research Survey (1999); Nagy and Furtan (1977, 1978); and Inventory of Canadian Agri-Food Research (1998, 2000). Yield index: Saskatchewan Agriculture and Food (n.d.); Nagy and Furtan (1978); Prairie Pools Inc. (n.d.); and authors' estimates based on Manitoba Crop Insurance Corporation (2002) and M. Hartman (personal communication, December 2002). Variety Classification: Saskatchewan Agriculture and Food (n.d.); CFIA (1998, 2002/2003); Alberta Agriculture and Food (2002/2003); Manitoba Agriculture and Food (2003); Paterson and Sons Limited Grain Buyer (2003); Alberta Seed Industry (2003); and Canola Council of Canada (2002/2003). Biotechnology variables: The HT and HYB variables take a value between 0 and 1; PBR variable takes the value of 0 before the PBR act came into force on August 1, 1990 (Canada Department of Justice, 2000), and 1 thereafter. Price and revenue variable: Saskatchewan Agriculture and Food (2002); Statistics Canada (2003); Canola Council of Canada (2002); L.R. White (personal communication, November 2002). Technical Use Agreement (TUA) fees: Canola Council of Canada (2002) and authors' estimates.*

In Model 1, we considered the following specification:

$$\begin{aligned} Y_{i,t}^{PV} = {} & \beta_{0i} + \beta_1 AR_{i,t-k}^{PV} + \beta_2 BR_{t-l} \\ & + \beta_3 OAR_{i,t-r}^{PV} + \beta_4 AR_{t-m}^{PUB} + \beta_5 OY_{i,t-h}^{PV} \\ & + \beta_6 Y_{t-g}^{PUB} + \gamma_i Y_{i,t-1}^{PV} + u_{i,t}, \; i = 1, \ldots, 5 \end{aligned} \tag{3}$$

$$\begin{aligned} Y_{j,t}^{PUB} = {} & \delta_{0j} + \delta_1 AR_{j,t-k}^{PUB} + \delta_2 BR_{t-l} \\ & + \delta_3 OAR_{j,t-r}^{PUB} + \delta_4 AR_{t-m}^{PV} + \delta_5 OY_{j,t-h}^{PUB} \\ & + \delta_6 Y_{t-g}^{PV} + \gamma_j Y_{j,t-1}^{PUB} + u_{j,t}, \; j = 1, 2 \end{aligned} \tag{4}$$

where we assume that $|\gamma_i| < 1$ and $|\gamma_j| < 1$ for all *i, j* to ensure stationary; $Y_{i,t}^{PV}$ is the annual weighted yield index of private firm *i* in year *t*; $Y_{j,t}^{PUB}$ is the annual weighted yield index of public firm *j* in year *t*; BR_{t-l} is the basic research expenditures in year *t–l* (same for all seven firms); $AR_{i,t-k}^{PV}$ is the private applied research expenditures of firm *i* in year *t–k*; $AR_{j,t-k}^{PUB}$ is the public applied research expenditures of firm *j* in year *t–k*; $OAR_{i,t-r}^{PV}$ is the total applied research expenditures of other private firms excluding firm *i* in year *t–r*; $OAR_{j,t-r}^{PUB}$ is the total applied research expenditures of other pubic firms excluding firm *j* at year *t–r*; AR_{t-m}^{PV} is the total applied research expenditures of private firms in year *t–m*; AR_{t-m}^{PUB} is the total applied research expenditure of public firms in year *t–m*; Y_{t-g}^{PV} is the annual weighted yield index of private firms at year *t–g*; Y_{t-g}^{PUB} is the annual weighted yield index of public firms at year *t–g*; $OY_{i,t-h}^{PV}$ is the total yield index of private firms excluding firm *i* in year *t–h*; $OY_{j,t-h}^{PUB}$ is the total yield index of public firms excluding firm *j* in year *t–h*; and $u_{i\,t}$ and $u_{j,t}$ are random error terms assumed to have multivariate normal with mean vector zero and covariance matrix.

Model 1 consists of a system of seven equations of seemingly unrelated regression: five for private firms and two for public firms. Some interesting practical features of the model are worth mentioning. First, each of the equations in the system contains its own lag of the dependent variable, so the system is dynamic and autoregressive in impacts. Second, given the limitation of the current data set, we have imposed cross-equation restrictions on both private and public firms. This enables us to adequately estimate the parameters of the system. Finally, we did not represent each equation with a general distributed lag model.[10] We chose a simpler lag structure, looking for a single lag for each variable, assuming that it will take at least six years from basic research and four years from applied research for impacts to be realized. Note, however, that any impacts will carry over to additional future periods through the lagged dependant variable in each equation.

Model 2 is specified as follows:

$$\begin{aligned} R_{i,t}^{PV} = {} & \alpha_{0i} + \alpha_1 AR_{i,t-k}^{PV} + \alpha_2 BR_{t-l} \\ & + \alpha_3 OAR_{i,t-r}^{PV} + \alpha_4 AR_{t-m}^{PUB} + \alpha_5 OY_{i,t-h}^{PV} \\ & + \alpha_6 Y_{t-g}^{PUB} + \alpha_7 HYB_{i,t}^{PUB} + \alpha_8 PBR_t \\ & + \alpha_9 TUREV_{i,t}^{PV} + \gamma_i R_{i,t-1}^{PV} + u_{i,t}, \; i = 1, \ldots, 5 \end{aligned} \tag{5}$$

$$\begin{aligned} R_{j,t}^{PUB} = {} & \theta_{0j} + \theta_1 AR_{j,t-k}^{PUB} + \theta_2 BR_{t-l} \\ & + \theta_3 OAR_{j,t-r}^{PUB} + \theta_4 AR_{t-m}^{PV} + \theta_5 OY_{j,t-h}^{PUB} \\ & + \theta_6 Y_{t-g}^{PV} + \theta_7 HYB_{j,t}^{PUB} + \theta_8 PBR_t \\ & + \theta_9 TUREV_{j,t}^{PUB} + \gamma_j R_{j,t-1}^{PUB} + u_{j,t}, j = 1, 2 \end{aligned} \tag{6}$$

where, we assume again, $|\gamma_i| < 1$, $|\gamma_j| < 1$, $|\rho_i| < 1$, and $|\rho_j| < 1$ for all i, j; $R_{i,t}^{PV}$ is the revenue of private firm i in year t; $R_{j,t}^{PUB}$ is the revenue of public firm j in year t; $HYB_{i,t}^{PV}$ is the proportion of the total area seeded to hybrid (*HYB*) varieties for private firm i at time t; $HYB_{j,t}^{PUB}$ is the proportion of the total area seeded to hybrid (*HYB*) varieties for public firm j at time t; PBR_t is the plant breeders' rights dummy for private/public firm in year t; $TUREV_{i,t}^{PV}$ is the TUA (technical use agreement) revenue for private firm i in year t; $TUREV_{j,t}^{PUB}$ is the TUA revenue for public firm j in year t; and other variables are as defined previously in Model 1.

The specifications of Model 2 are similar to those of Model 1 in terms of lag structure specifications. For each model, the unknown parameters in the dynamic system, in principle, can be easily estimated by Zellner's Iterative SUR (ISUR) estimator.[11] These estimates are consistent, asymptotically efficient, and numerically equivalent to the maximum likelihood estimator.

One estimation decision that arises in each model is how to choose the appropriate lag length. One simple way is to select the lag based on the minimum of the multivariate version of the Akaike Information Criterion (MAIC). Alternatively, given a special structure of the model, specifying different lags always results in the same number of the parameters. Consequently, minimizing the MAIC is equivalent to minimizing the determinant of residual covariance matrix. We have used this second approach to determine the appropriate lag length in each model.

Regression Results

The regression results for the two models (Tables 1 & 2) appear to be robust. Most of the estimated coefficients are individually statistically significant at the 5% level. Almost all the explanatory variables have the expected signs. The regressions have $\bar{R}^2$ between 0.590 and 0.997 (first regression) and 0.467 and 0.963 (second regression).

Model 1. The firms' own-lagged applied research expenditure has a positive effect on yield. The coefficient of 2.12 for private firms (0.601 for public firms) implies that a \$1 million expenditure increases the yield index by 2.12 (0.601). The much larger coefficient for the private firms suggests a higher direct productivity for private applied research. For all firms, public and private, the previous years' yields have positive signs with coefficients less than one, and thus are consistent with dynamic stability.

The empirical results reveal that lagged basic research expenditure positively affects the annual weighted yield index of private firms while negatively affecting the weighted yield index of public firms. Public basic research expenditure with a lag of nine periods has a coefficient of .304 in the first model, implying that *ceteris paribus*, a \$1 million increase in the annual public basic research in one year increases the private yield index after nine years by .304 index points. This positive spillover is consistent with notion that basic research increases the productivity of private applied research. In contrast to this result, a \$1 million increase in the annual public basic research expenditure in one year reduces the public yield index after nine years by .2 index points. This interesting result suggests that an increase in basic research—which is located within public institutions—uses common resources within the research institution, thereby reducing the resources available for applied public research.

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10. *We tried to specify a more general system of autoregressive distributed lag model (SADL), and we did not find any significance for these lag structures.*
11. *The ISUR estimator uses equation-by-equation OLS to construct an estimate of the disturbance covariance matrix Ω and then does the generalized least squares, given this initial estimate of Ω, on an appropriately stacked set of equations. The procedure is then iterated until the estimated parameters and the estimated Ω converge.*

Table 1. Regression results of Model 1.

Variable	Expression	Coefficient	*t*-statistic	Prob.
Private applied research expenditures in year *t–6*	$AR^{PV}_{i,t-k}$	2.116	8.171	0.000
Basic research expenditures in year *t–9*	BR_{t-l}	0.304	3.326	0.001
Total applied research expenditures of other-private firms in year *t–6*	$OAR^{PV}_{i,t-r}$	0.320	3.813	0.000
Total applied research expenditures of public firms in year *t–7*	AR^{PUB}_{t-m}	0.158	1.831	0.069
Total yield index of private firms in year *t–6*	$OY^{PV}_{i,t-h}$	0.903	65.945	0.000
Yield index of public firms at year *t–12*	Y^{PUB}_{t-g}	–0.448	–5.600	0.000
Public applied research expenditures in year *t–6*	$AR^{PUB}_{j,t-k}$	0.601	2.087	0.038
Basic research expenditures in year *t–9*	BR_{t-l}	–0.200	–1.734	0.085
Total applied research expenditures of other-public firms in year *t–6*	$OAR^{PUB}_{j,t-r}$	0.351	3.320	0.001
Total applied research expenditures of private firms in year *t–7*	AR^{PV}_{t-m}	–0.163	–2.018	0.045
Total yield index of other-public firms in year *t–6*	$OY^{PUB}_{j,t-h}$	0.036	2.297	0.023
Yield index of private firms at year *t–12*	Y^{PV}_{t-g}	0.000	–0.317	0.752
Yield index of private firm 1 in year *t–1*	$Y^{PV}_{1,t-1}$	0.067	4.221	0.000
Intercept private firm 1	constant	37.665	5.128	0.000
Yield index of private firm 2 in year *t–1*	$Y^{PV}_{2,t-1}$	0.335	3.761	0.000
Intercept private firm 2	constant	54.000	4.927	0.000
Yield index of private firm 3 in year *t–1*	$Y^{PV}_{3,t-1}$	0.479	6.419	0.000
Intercept private firm 3	constant	48.706	4.758	0.000
Yield index of private firm 4 in year *t–1*	$Y^{PV}_{4,t-1}$	0.500	7.431	0.000
Intercept private firm 4	constant	42.836	4.491	0.000
Yield index of private firm 5 in year *t–1*	$Y^{PV}_{5,t-1}$	0.500	6.697	0.000
Intercept private firm 5	constant	47.323	4.712	0.000
Yield index of public firm 1 in year *t–1*	$Y^{PUB}_{1,t-1}$	0.521	5.251	0.000
Intercept public firm 1	constant	50.287	4.858	0.000
Yield index of public firm 2 in year *t–1*	$Y^{PUB}_{2,t-1}$	0.940	14.495	0.000
Intercept private firm 2	constant	–0.615	–0.131	0.896

Note. Dependent variables: annual weighted yield index of private firms i in year t : $Y^{PV}_{i,t}$*; public firms:* $Y^{PUB}_{j,t}$ *. Determinant residual covariance: 1.71E+12.* $\bar{R}^2$ *: 0.590 – 0.997.*

Table 2. Regression results of Model 2.

Variable	Expression	Coefficient	*t*-statistic	Prob.
Private applied research expenditures in year *t–9*	$AR^{PV}_{i,t-k}$	0.480	1.854	0.065
Basic research expenditures in year *t–7*	BR_{t-l}	0.346	2.777	0.006
Total applied research expenditures of other-private firms in year *t–9*	$OAR^{PV}_{i,t-r}$	–0.341	–1.852	0.066
Total applied research expenditures of public firms in year *t–8*	AR^{PUB}_{t-m}	0.311	2.725	0.007
Total yield index of other-private firms in year *t–9*	$OY^{PV}_{i,t-h}$	–0.309	–6.477	0.000
Yield index of public firms at year *t–12*	Y^{PUB}_{t-g}	–0.305	–2.663	0.009
The proportion of the total area seeded to hybrid (HYB) varieties for private firm at time *t*	$HYB^{PV}_{i,t}$	3.466	2.678	0.008
Plant Breeders' Right dummy for private/public firm in year *t*	PBR_t	5.592	2.992	0.003
TUA (technical use agreement) revenue for private firm in year *t*	$TUREV^{PV}_{i,t}$	0.943	11.966	0.000
Public applied research expenditures in year *t–9*	$AR^{PUB}_{j,t-k}$	0.962	3.231	0.002
Basic research expenditures in year *t–7*	BR_{t-l}	–0.187	–0.639	0.524
Total applied research expenditures of other-public firms in year *t–9*	$OAR^{PUB}_{j,t-r}$	–2.412	–4.159	0.000
Total applied research expenditures of private firms in year *t–8*	AR^{PV}_{t-m}	0.278	1.050	0.295
Total yield index of other-public firms in year *t–9*	$OY^{PUB}_{j,t-h}$	0.247	1.816	0.071
Yield index of private firms at year *t–12*	Y^{PV}_{t-g}	0.00022	–2.740	0.007
The proportion of the total area seeded to hybrid (HYB) varieties for public firm at time *t*	$HYB^{PUB}_{j,t}$	–3.996	–0.842	0.401
Plant Breeders' Right dummy for private/public firm in year *t*	PBR_t	–8.140	–1.628	0.105
TUA (technical use agreement) revenue for public firm in year *t*	$TUREV^{PUB}_{j,t}$	7.738	1.393	0.165
Revenue of private firm 1 in year *t–1*	$R^{PV}_{1,t-1}$	1.199	7.258	0.000
Intercept private firm 1	constant	24.777	2.377	0.019
Revenue of private firm 2 in year *t–1*	$R^{PV}_{2,t-1}$	0.412	3.763	0.000
Intercept private firm 2	constant	25.347	2.434	0.016
Revenue of private firm 3 in year *t–1*	$R^{PV}_{3,t-1}$	0.882	14.516	0.000
Intercept private firm 3	constant	22.105	2.115	0.036
Revenue of private firm 4 in year *t–1*	$R^{PV}_{4,t-1}$	0.497	6.137	0.000
Intercept private firm 4	constant	25.885	2.492	0.014

Table 2. (continued) Regression results of Model 2.

Variable	Expression	Coefficient	*t*-statistic	Prob.
Revenue of private firm 5 in year *t–1*	$R^{PV}_{5,t-1}$	0.636	10.483	0.000
Intercept private firm 5	constant	25.844	2.484	0.014
Revenue of public firm 1 in year *t–1*	$R^{PUB}_{1,t-1}$	0.437	3.428	0.001
Intercept public firm 1	constant	41.328	4.419	0.000
Revenue of public firm 2 in year *t–1*	$R^{PUB}_{2,t-1}$	0.383	2.714	0.007
Intercept private firm 2	constant	–16.897	–1.160	0.248

Note. Dependent variable: revenue of private firm i in year t: $R^{PV}_{i,t}$ *public firm j in year t:* $R^{PUB}_{j,t}$ *. Determinant residual covariance: 6.83E+08,* $\bar{R}^2$ *: 0.467 – 0.963.*

Other firms' lagged research expenditures have a spillover effect on each firm's yield index. The synergistic effect was strongest within groups—between public firms (.35) and between private firms (.32). A somewhat smaller synergistic affect was evident between groups in the spillover of public expenditure on applied yields (.158). These positive effects are consistent with human capital and knowledge spillovers. A negative spillover effect of .163 occurred between private firm expenditures and public firm yields. This latter between-group effect may have been generated from private firms bidding highly qualified personnel away from the public sector. During the growth phase of the industry, migration tended to occur from the public sector to the private sector.

A positive spillover was evident for within-group yields while the spillover was negative between groups. A one-point increase in other-private (public) firms' yield index resulted in a .9 point (.036) increase in the firm's own-yield index. In contrast, the public yield index had a negative .448 point impact on private yield, while the reverse between-group impact was also negative but insignificant.

The results of Model 1 show that a firm's current yield index can be modeled as a function of previous research expenditure. The model revealed strong evidence of positive spillovers within the public and within the private sectors. Publicly funded basic research and applied research created a positive spillover for private yields. Other-public/private spillovers were negative in sign.

Model 2. Model 2, which examines the determinants of firm revenue, revealed that one dollar of own-firm lagged applied research increased private (public) revenue by $.480 ($.962). This model also showed important spillover effects. In this case the spillovers include pecuniary effects in the output market and therefore illuminate crowding effects. An additional dollar in lagged basic research expenditure changed private (public) revenue by $.346 (–$.187), indicating that public basic research provides monetary benefits to private industry while drawing resources away from public-firm applied research.

The interfirm spillover effects of lagged applied research were negative within groups. A dollar increase in other-private (public) firm applied research expenditure reduced firm revenue by $.341 ($2.412). Given that there were positive spillovers in production, these negative impacts show a strong degree of competition within groups; this result is not surprising, because the firms are competing for the same customers.

In contrast to the within-group competition, a $1 increase in public (private) expenditure increased private revenue by $.311 ($.278), indicating positive spillovers between groups. This indicates that nonpecuniary spillovers dominate the pecuniary spillovers such that public applied research activity has crowded in private research, rather than crowding it out.

The spillover of other-firms' yields tends to have a negative impact on firm revenue. This negative relationship exists among private firms, from private to public firms, and from public to private firms. The exception is the public-to-public interaction, where there is synergistic impact, perhaps due to a different ethos among public breeders.

The variables for proportion of the total area seeded to hybrids and for plant breeders' rights had a positive impact on private revenues, while having a negative impact on public revenue. A complete shift to hybrids would increase (reduce) private (public) revenue by $3.466 million ($3.996 million) per year. PBR increased (reduced) private (public) revenue by $5.592 million ($8.14 million). The TUA fees had a positive affect on total revenue, .94 in the case of private firms, suggesting a slight reduction in the non-TUA revenue; for the public firms a dollar in TUA revenue tended to increase total revenue by $7.738, indicating a dramatic increase in pricing.

In summary, Model 2, which examines firm revenue, shows evidence of the pecuniary impacts of competition between firms, particularly within groups. Applied within-group expenditure reduces other-firm revenue, while between-group spillovers are positive. A higher lagged yield for competing firms has a negative impact on revenue, with the exception of public-to-public impacts, for which it is positive. Property rights and hybrid technologies have a positive effect on private sales revenue and a negative impact on public revenue.

Conclusions and Policy Implications

This study examined many research spillovers in a modern crop research industry as delineated by: their public or private source; their public or private incidence; whether they were generated through basic research, applied research activity, or germplasm; and whether they were interfirm pecuniary, or interfirm nonpecuniary in nature. The empirical framework, which estimated a production function and a private revenue function, provided a useful conceptual separation of research spillovers and a broad scope of empirical results with many implications for private incentives and research policy.

The two empirical models fit the data well and provided theoretically plausible estimates. Lagged applied research investment by each firm increased research output and revenue. Enhanced IPRs increased private research revenue. Perhaps the most striking general result was the ubiquitous presence of research spillovers in both models.

The empirical results of Model 1 provide the strongest evidence of nonpecuniary spillovers. The results show that public basic research, public applied research, and other-firm private applied research, and other private firm varieties created a positive spillover for private firms. These spillovers indicate that public research has made private research firms more productive, and private firms may benefit from the knowledge generated from their rivals.

The empirical results of Model 2 provide estimates of the total (pecuniary plus nonpecuniary) research spillovers. The results show that although private firms have a net competitive or "crowding-out" effect, public-firm basic and applied research enhances private revenue, creating a "crowding-in" effect. This model also shows that plant breeders' rights, proprietary technologies, and technical use agreements enhance private firms' ability to generate revenue.

The results of the empirical analysis have several implications for research policy. The most apparent is that public and private research firms are integrally linked through numerous types of research spillovers. Publicly funded basic and applied research both had positive effects on private research productivity and profitability. The negative impact of basic research on public firm output and revenue suggests that these basic research activities are underreported and tend to use resources earmarked for applied research. Given the importance of basic research to private industry output, this diversion of resources could be optimal. The ability of public institutions to do applied research while crowding-in private applied research suggests that public policies, such as the Matching Investment Initiative, have been successful in mitigating the normal crowding effects. The positive impact that IPRs had on private revenue suggests that these changes have been effective in providing incentives for private research.

The prevalence of nonpecuniary interfirm research spillovers suggests a strong research clustering effect—an effect that is particularly evident in Saskatoon, Saskatchewan, where there is a significant concentration of public and private firms involved in canola research. The existence of a clustering effect suggests the need for a mechanism for the coordination of private and public location choices to maximize the spillover opportunities. The significant public-to-private spillovers emphasize the importance of the public institutions in these clusters.

In this study, we found empirical evidence of a variety of research spillovers in the canola research industry. The importance of research to economic growth suggests a need to fully understand these complex nonmarket relationships and to manage research policy with these spillovers in mind.

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