EXECUTIVE SUMMARY

Until recently crop research in Canada was performed predominantly by the public sector. Over the last decades, however, crop research industry has experienced significant changes in the funding and control of research. Governments are re-prioritizing research investment and directing more dollars away from crop development research toward efforts seen as more novel, further up the value chain or providing quick payoff (Meristem (2005)). Public research funding, in particular that for wheat and barley, has been declining over the past 10-15 years (Meristem (2005)). The question who should fund and control cereal research and wheat in particular is a matter of current debates. In order to propose a certain path for the government research policy it is important to know how publicly financed wheat research industry has performed until now.

Past studies have provided compelling evidence that public cereal research in Canada has high investment value. A range of independent studies show a minimum 10-fold return on cereal development research (Meristem (2005)). Guzel, Furtan and Gray (2005) identified a minimum four-to-one return on investment in wheat breeding and twelve-to-one return for barley breeding. These numbers need updating and the objective of this working paper is to provide an updated estimate of the returns to wheat research in Western Canada over 1977-2006.

Studies estimating returns to wheat breeding in Canada in the past have assumed that research expenditures yield benefits for 8-12 years, the time period that a variety is on farmers’ fields. However, a unique feature of plant breeding is that it derives the material
from the existing germplasm stock generated by the past breeding programs. Even when the variety losses its attractiveness to farmers it can be used as input into the future breeding programs, thus contributing to the development of next-generation high-yielding varieties. Furthermore, in their breeding programs researchers are extensively using knowledge created long ago. This is especially true for wheat since it has not experienced a drastic change in breeding techniques associated with the biotechnology revolution. Therefore, when analyzing the rates of return to wheat breeding it is important to allow for the effect of current breeding programs on breeding programs twenty, thirty or even more years from now. A unique feature of the model we are employing in this paper is that it allows us to capture the total stream of benefits from wheat breeding research that goes more than 50 years into the future.

In this study the effect of wheat breeding on production is modeled through its impact on average yield. The relationship between the average weighted wheat yield index and past R&D expenditures is specified as an infinite distributed lag model, which is estimated econometrically. Two lag structures are assumed for the lagged R&D coefficients - the Modified Almon Distributed Lag (MADL) and Geometric Combination Lag (GCL).

The results reveal that one professional scientist in wheat breeding contributes to an increase in the average yield index in the long run by 0.69 index points when the MADL structure is imposed and 0.61 index points when the GCL structure is assumed. Use of the estimated coefficients in the calculation of the marginal rates of return produces the internal rate of return to one professional scientist in the 43-53% and 35-41% range, depending on the cost of one professional person year and elasticity assumptions, for the MADL and GCL models, respectively. Such high rates of return indicate that investment into wheat breeding has shown to be highly beneficial and would warrant continued public support to the wheat research industry.
1. **Introduction**

Canada has a long history of investing in wheat research with the first research station established in Ottawa in 1886. Since its outset wheat research in Western Canada has been performed primarily by the public sector - government institutions and universities. The argument for public funding was that, in its pure form, knowledge is a “public good”, that is, no one can be excluded from using it, which undermines the ability of innovators to appropriate the rewards. Only very recently has the private sector begun to significantly invest in wheat research with an interest in developing herbicide-tolerant varieties (Gray and Malla (2000)).

Breeding for yield, quality and pest resistance in the past hundred of years cannot go unrecognized. Wheat research combined with the changes in transportation and handling systems contributed to the creation of a strong wheat economy in Western Canada. Wheat has become a major crop on the prairies and nowadays Canada is the sixth world’s largest producer of wheat and the second largest exporter of wheat. Due to high quality standards on the international market Canada has gained a standing of a high-quality grain supplier.

Agricultural research yields a high pay-off to society. This has been supported by the numerous empirical studies where the returns to agricultural research have been documented to range from 30 to 130%. In particular, studies on benefits from wheat research in Canada indicate that the rates of return are as high as 40% (Zentner and Peterson (1984), Klein et al. (1996)). Nevertheless, in spite of such reassuring estimates wheat research industry has not been drastically expanding over the last decades and in some cases it has even been shrinking. In a world where funds are scarce and ways to cut budget expenditures are sought for, productivity and allocation of research expenditures are becoming important issues for planners and policy makers and effectiveness of R&D spending gets questioned. What also complicates matters is the time gap between research outlays and benefits: very often policy makers are short-sighted and cannot see the benefits that research brings decades later after it had been undertaken. This contributes to the underestimation of the research benefits and as a result underinvestment in agricultural research.

This paper is intended to yield updated information on the levels of pay-off to wheat breeding in Western Canada. The model we are employing in this study allows to capture the total stream of benefits from wheat breeding research that goes more than 50 years into the future.

This paper is organized in 6 sections. In section 2 we provide an overview of the wheat industry in Canada. Section 3 and 4 deal with the wheat variety development in Canada - the history of wheat breeding and the existing restraints to breeding superior varieties. Section 5 provides a brief overview of the literature on rates of return to wheat research in
Canada. Section 6 contains the description of the methodology employed in this study, the description of the data and data sources as well as presents the estimates of the rates of return to wheat breeding in Western Canada. Section 7 concludes the chapter.

2. Wheat sector overview

Canada has a long history of wheat production with the first wheat grown in Quebec city in the early 17th century. In the nineteenth century wheat production in Eastern Canada (Ontario) gained more significance for settlers and wheat became a dominating crop in agriculture. During this period wheat production faced a lot of problems among which deceases (stem rust and smut) and pests (Hessian fly, wheat midge and chinch bugs) were the major ones. A turning point in wheat production was the development of the cultivar Red Fife in the mid-19th century. It was developed by an Ontario farmer, David Fife from the seed he received from his friend in Glasgow. Due to its resistance to rust and high yield Red Fife quickly spread from farmer to farmer and became the major spring wheat cultivar grown in Canada. The introduction of Red Fife combined with improvements in transportation and handling systems contributed to the expansion of wheat production in Ontario. By 1880 Ontario was producing approximately 254,000 tons of winter wheat and 100,000 tons of spring wheat. After 1880 the importance of wheat production in Ontario started to decline (Campbell & Shebeski (1986)).

In Western Canada wheat industry developed much later. The first attempts to grow wheat date back to 1812. However, due to weather conditions and pest problems wheat production in the prairies failed periodically. It was not until late 1870s that Red Fife reached Western Canada and this launched a strong wheat industry in the prairies. Spreading of Red Fife was complemented by railway, land and immigration policies that encouraged settlement in Western Canada, thus contributing to the establishment of the wheat economy. In Manitoba 235,000 hectares were planted to grain crops in 1885 and this number more than tripled by 1900 (Campbell & Shebeski (1986)). Wheat rapidly became the most important crop grown in Saskatchewan, reaching four million hectares by 1919. Nowadays, prairie provinces produce about 97% of wheat in Canada.

Establishment of the wheat breeding sector that started with the foundation of the Central Experimental Farm in Ottawa in 1886 allowed further development of decease and pest resistant cultivars. This contributed to a rapid expansion of the wheat economy and made Canada one of the world’s largest producers. Averaged over a ten-year period Canada is the world’s sixth largest producer and the second largest exporter of wheat. Total wheat production since 1980 ranged from about 16 mln. tons to 33 mln. tons. As can be seen from Figure 1 most of wheat production is concentrated in Prairies.
Depending on end-uses of wheat it is divided into market classes that have different quality characteristics such as protein content and gluten strength. In Western Canada there are 8 wheat classes: Canada Prairie Spring Red (CPSR), Canada Prairie Spring White (CPSW), Canada Western Amber Durum (CWAD), Canada Western Extra Strong (CWES), Canada Western Hard White Spring (CWHWS), Canada Western Red Spring (CWRS), Canada Western Red Winter (CWRW) and Canada Western Soft White Spring (CWSWS). Spring wheat accounts for about 85% of total wheat production in Western Canada with Prairies producing 70-80% of Canada’s spring wheat. Among spring wheats the most common is hard red wheat and in Western Canada it comprises 85% of spring wheat production. The CWRS wheat class is considered a high-protein premium bread wheat. The CPS class was created in 1985 with the registration of the variety HY320. This class of wheat is characterized by a protein content that is 1-1.5% lower than that of the CWRS wheat class and is intended for use by markets that don’t require a premium high-protein product. In recent years, CPSR varieties have been extensively used as feed in livestock production and starch in ethanol production. Soft white and Extra Strong wheats have been grown on a limited scale since Canada lost the markets for these classes.
The domestic market for Canadian wheat is limited and Canada exports about 15 mln. tons annually (Figure 3) with its share accounting for about 21% on the world market for wheat exports\(^1\).

3. WHEAT VARIETY DEVELOPMENT IN CANADA

Wheat breeding was launched in Canada in 1986 with the establishment of the Federal Experiment Farm System in Ottawa. A cross-breeding program in wheat was initiated two years later and almost twelve years later the new cultivar Marquis was developed from the cross between Red Fife and Hard Red Calcutta and distributed to Canadian farmers in 1999. This cultivar quickly replaced Red Fife and became the dominant variety grown in the prairie provinces (Campbell & Shebeski (1986)).

As new races of rust were developing and the existing plants became susceptible to deceases there was a need to develop new rust resistant cultivars. Wheat breeding industry was expanding and by 1954 a number of stem rust resistant cultivars were developed, which helped take stem rust under control. At about that time, however, a new problem appeared that endangered the wheat economy in the prairies - huge proportions of grain harvest were damaged by sawfly. The first solid stem cultivar resistant to the wheat stem sawfly was

\(^1\)Statistics Canada
developed by the Swift Current Research Station and released in 1946 (Campbell & Shebeski (1986)).

One should not underestimate the contribution of the wheat breeding industry. Over the last hundred of years more than sixty new cultivars were developed. Breeding efforts have been directed to breeding for yield, quality, pest resistance and general agronomic traits.

Even though wheat yield is an important characteristic of a crop as long as grain producers are concerned wheat breeding for yield have limited success. This is explained by the fact that grain yield is a very complex trait that is closely interrelated with other characteristics of wheat. Grain yields are usually associated with lower protein concentration and minimum value of protein concentration required to meet the quality standards effectively limits maximum yields. Higher yields are also associated with a delay in crop maturity. Given a very short frost-free period in the Prairies the development of early maturing rather than higher-yielding varieties has been a priority in plant breeding.

Despite extremely harsh weather that kills a lot of diseases and pests farmers in the prairie provinces have been facing significant losses due to pests and diseases. It is estimated that about 20% of the wheat harvest is lost each year for this reason and this made breeding for pest resistance one of the most important objectives in developing new varieties (Gray and Malla (2000)). In order to control leaf and stem rust the federal Rust Laboratory at Winnipeg was established over 60 years ago. The type of resistance used in breeding for rust
resistance on the prairies is referred to as specific resistance, which makes wheat resistance to some races of rust but not to others (Knott (1986)). Breeding efforts have also been undertaken to control common root rot, loose smut and bunt and ergot. In general breeding for pest resistance has been successful and currently most of the cultivars have adequate resistance to most diseases. However, a continuous breeding effort is required to deal with the evolution of new races. This is especially important in the light of the recent emergence of UG99, a deadly form of leaf rust that now threatens global wheat production.

The process of wheat breeding is lengthy and complex. Plant breeders generate new material using available germplasm. Newly created material is evaluated in field conditions for basic characteristics such as yield, days to maturity and disease resistance. After 2 or 3 rounds of seed multiplication the most advanced lines proceed to the “A” series field trials where quality screening is carried out. Lines that survive through this screening proceed to the “B” series field trials. After the “B” trials the material undergoes “Co-operative testing” over 3 years (the “C” field trials). The advanced material from these trials is sent to the Grain Research Laboratory in Winnipeg where samples are thoroughly evaluated for conformity to the kernel characteristics of each grain class and tested for over 30 quality parameters. In February each year the lines are discussed at the Prairie Registration Recommending Committee for Grain (PRRCG) meetings where the lines that meet agronomic, quality and disease characteristics are offered for registration. The Canadian variety development system is summarized in Figure 4.

Nowadays, wheat breeding industry in Western Canada is represented by 7 major institutions: the University of Saskatchewan, University of Manitoba, University of Alberta, Semiarid Prairie Agricultural Research Centre in Swift Current (AAFC), Cereal Research Center in Winnipeg (AAFC), Lethbridge Research Center (AAFC), Alberta Agriculture, Food and Rural Development in Lacombe. Breeding programs at the University of Saskatchewan include Canada Western Red Spring, Canada Western Extra Strong, Canada Western Hard White, Canada Western Amber Durum, Canada Prairie Spring, Canada Western Red Winter, feed and specialty wheats. University of Manitoba breeding programs include Canada Western Red Winter, Canada Western Red Spring and Canada Western Extra Strong. Recently the programs have been focusing on the transfer of tan spot resistance and the development of Fusarium Head Blight-resistant germplasm. Breeding programs at the AAFC centers encompass all wheat classes with an emphasis on developing high-yielding cultivars of Canada Western Hard White wheat with built-in genetic resistance to decesses and highly decease and lodging resistant cultivars for the Eastern prairie. The breeding program in Lacombe focuses on winter wheat and adaptation to the northern prairies, particularly the
If non-registered varieties are grown they can be qualified only as feed grains regardless of their quality parameters.

4. Registration of new varieties and restraints to breeding superior varieties

Today for a variety to be registered in Canada it must meet regulations of the Seeds Act in terms of purity, uniformity and distinguishability and it must meet the grading specifications outlined in the Canada Grain Act. For many years Canada has had a compulsory wheat classification system based on specific end uses of wheat and in Western Canada wheat is segregated according to visual characteristics such as size, shape and colour. The requirement for each class of wheat to have a specific and unique visual profile is known as the kernel visual distinguishability requirement (KVD). If a variety has been registered it must have complied with all the quality standards. To ensure the purity of wheat classes in the bulk handling system and prevent the contamination of a particular class of wheat with wheats

Central Parkland and Peace River regions of Alberta. Key emphases are cold tolerance, straw strength and resistance to powdery mildew.

**Figure 4.** The process of wheat breeding
that are visually indistinguishable from this class but have different quality parameters all
non-registered varieties can be classified only as feed grains regardless of their quality profile.

Due to strict quality assurance system, in particular protein level and gluten strength, Canada has gained a high standing on the international wheat market. Some players in the grain industry, however, assert that legislative initiatives aimed at sustaining Canada’s reputation for high quality wheat come at a very high cost. The existing variety registration system is believed to have blocked the adoption of a number of high-yielding varieties because they didn’t comply with some of the quality standards specified in the Canadian system, which in fact were of no relevance for the end-users of wheat. In particular, the requirement for the varieties to be visually distinguishable is considered to be a hindrance to the introduction of new varieties in Western Canada. The wheat breeder from the University of Manitoba, Anita Brule-Babel, indicated that “within the winter wheats, the KVD reports where things fail they almost always fail because they have a red spring kernel type within the mixture of the grain” (FarmScape (2006)) and another breeder stressed that: “Winter wheat breeders have not had a new hard red winter wheat variety supported for registration for 5 years because all their material is failing KVD requirements” (CSTA (2006)). A plant breeder, Dr. B. Cambell suggested that Canada sacrificed about 5% of potential yield due to the KVD requirement (Oleson (2003)). KVD is one more element to be considered and incorporating it into the breeding program is analogous to breeding for an additional trait, which takes extra time and effort. Oleson (2003) provided an estimate of yield increase in the case of KVD removal (Table 1).

<table>
<thead>
<tr>
<th>% Yield increase</th>
<th>Research</th>
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<tbody>
<tr>
<td>CWRS/BW (All current varietal requirements plus(^a))</td>
<td>3.0 to 4.0</td>
</tr>
<tr>
<td>CWRS/BW (Selective changes or flexibility(^b))</td>
<td>5.0 to 7.0</td>
</tr>
<tr>
<td>High Yielding (HY)(^c)</td>
<td>20.0 plus</td>
</tr>
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\(^a\)With the removal of KVD some requirements may be added to the current varietal registration requirements such as size, configuration and colour

\(^b\)Allowing for quality flexibility (not including protein content) to target a DNS class

\(^c\)These numbers incorporate a strategic direction of “going for feed”


It should be mentioned that while visual distinguishability is a requirement in Western Canada it is not like this throughout Canada and it does not exist in the US, the greatest competitor of Canada on the world wheat market. In Ontario, for example, KVD was removed in 1989 and since then the seed industry experienced a noticeable expansion in terms of research investment and the number of new varieties released (CSTA (2006)).
In June 2006 the Canadian Grain Commission announced plans to restructure western Canada’s wheat classes to allow the development and registration of non-milling wheat varieties. The changes are scheduled to take effect August 1, 2008 and will include the creation of a new general purpose wheat class and the elimination of kernel visual distinction requirements for the minor wheat classes (FarmScape (2006)).

5. Literature review: the benefits from wheat research

Because of the public good nature, undertaking agricultural research has long been considered the responsibility of governments. Prior to 1980s agricultural research was mostly performed by public sector. Even though agricultural research is perceived to yield social benefits in the form of productivity or quality improvements, under the prevailing economic climate the returns from and efficiency of public investments are being questioned and the public sector is withdrawing resources from agricultural sector. To show the importance of public R&D investments an extensive body of empirical literature that estimates the social benefits from public R&D expenditures has been generated. For the purpose of this study we will only review the papers that estimated the benefits of wheat research in Canada.

Zentner and Peterson (1984) quantify the benefits from public investment in wheat research in Canada by econometrically estimating the production function and its shifts attributable to all-wheat research. They find that annual social benefits from public wheat research are substantial averaging at $49 million over 1946-1979 (in real 1946 terms), with producers capturing 62% of the benefits. The results also reveal that each dollar invested in wheat research produced an average annual return of 30-39%.

Klein et al. (1996) extend the above study to disaggregate the different types of public wheat research to allow estimation of benefits from yield-increasing research only. They use a multi-crop mathematical programming model of Canadian agriculture to develop the estimates. The results suggest that with the fairly constant research expenditures of about $3 million per year (in real 1991 terms) the benefits ranged from less than $10 million in 1972 to more than $390 million in 2001, with 80% of the benefits accruing to producers. The internal rate of return to yield-increasing investments, estimated by the authors, ranges from 27.4% to 38.9% depending on the case situations.

Guzel, Furtan and Gray (2005) estimate the benefits from Western Grains Research Foundation (WGRF) wheat and barley check-offs that started in Canada in 1994. They employ consumer-producer surplus framework to estimate the benefit/cost ratio and the rates of return. The rate of return was calculated based on the difference between the factual scenario (the observed prices and quantities) and the counterfactual scenario in which the authors identified the breakthrough varieties developed with the WGRF funds and calculated the
yield improvement that would not have been achieved had there been no check-off program in place. The research yielded a value of the benefit/cost ratio of 4.4 for wheat, which means that every dollar invested in wheat research generates $4.4 in benefits. The corresponding rate of return to wheat breeding was at 23.8%.

6. Estimating benefits from wheat breeding in Western Canada

The primary objective of this chapter is the estimation of rates of returns to wheat breeding in Western Canada. In the empirical literature the benefits of research have been estimated in a number of different ways. The most common approaches employed include estimating research induced supply shifts in the production function or cost function frameworks and estimating the effect of R&D on total factor productivity in agriculture.

Measuring the benefits from research is not a simple task and it is complicated by the dynamic structure linking research expenditures, knowledge stock and benefits. Figure 5 depicts the phases of crop breeding (research) (Alston et al. (2000)). Initially there are only costs associated with breeding effort as breeders incorporate new traits into crops and undergo the testing procedures. In plant breeding it takes about 10-15 years from the beginning of a breeding project until registration is granted and the variety is released to farmers. The phase before which the benefits start occurring is called the gestation period and during this phase the net benefits from research are negative. Once the variety (or innovation, in general) is released to farmers the new phase starts - the adoption phase. As the innovation spreads out the benefits from breeding/research build up and eventually the net benefit becomes positive. At some point the adoption reaches its maximum, after which the benefits from the new technology start declining. In some cases the flow of benefits may continue for a very long time and this is particularly true in plant breeding. Even when varieties get obsolete, which means that they are not commercially grown anymore and there are no direct benefits from adoption of these varieties, they can be used as a source of germplasm in future breeding programs. For instance Marquis wheat released in 1909 continues to be in the parent material of every variety bread wheat grown in western Canada grown in 2008. Thus, a breeding program not only generates benefits in the form of a superior (higher yielding or more disease-resistant) variety that comes directly out of the program but also contributes to the accumulation of knowledge and germplasm stock that can be used in future breeding programs. The duration of the period over which benefits attributable to a particular breeding program will be extracted will depend on the rate of knowledge and germplasm depreciation. Even though knowledge does not depreciate, its utilization, and, hence the relative stock of knowledge may change (Alston, Craig and Pardey (1998)).
Modelling the linkage between breeding effort and benefits requires good understanding of how innovations affect production and how the stock of knowledge and contributions to the stock of knowledge affect production. In this study we will model the effect of wheat breeding on production through its effect on average yield. The theoretical framework follows the one outlined in Malla, Gray and Phillips (1999). If varieties follow some particular pattern of adoption then the weighted average yield index in year $t$, $Y_t$, will be a weighted average of the varieties introduced in previous years and that are still being sown by farmers. Thus,

$$Y_t = \sum_{i=0}^{n} \gamma_i y_{t-i}$$

where $\gamma_i$ is the proportion of area grown to varieties $i$ years after introduction, $y_{t-i}$ is the weighted average yield of the varieties introduced in previous years.

Every new variety is a result of the breeding effort over the preceding 10-15 years. The breeding process is unique in a sense that the development of new variety incorporates the use of the existing varieties as a germplasm source and knowledge embodied in varieties developed earlier. Thus, the outcome of a breeding program can be written as follows:

$$z_t = f(B_{t-g}, G_{t-g-n}, K_{t-g})$$

where $n$ is the number of years a breeding program takes to complete, $g$ - gestation lag, $z_t$ - the result of the breeding program such as, for example, quality or yield of the variety produced in year $t$, $B_t$ - is the breeding effort directed at producing that specific variety, $G_{t-n}$ - previously developed germplasm (high-yielding or decease-resistant varieties developed prior to the year when the breeding program was launched) that is used in developing the variety and $K_{t-g}$ -
is the stock of knowledge existing at the time when the variety was being developed. Since
new variety is a result of many years of work the breeding effort can be represented as a
function of breeding expenditures over a number of years:

\[ B_{t-g} = f(E_{t-g}, E_{t-g-1}, \ldots, E_{t-g-n}) \]

where \( E_{t-g-i} \) are breeding expenditures in year \((t - g - i)\).

High-yielding or disease-resistance varieties used as a germplasm source in the breeding
program are the result of the breeding programs undertaken in the past. The speed at
which germplasm becomes obsolete will depend on a number of factors such as the ability of
pests and deceases to adapt to new conditions and that will determine for how many years
the developed germplasm (varieties) can be used as a source of variation in future breeding
programs. Thus, germplasm stock existing at the time when the new breeding program takes
off can be written as a function of past breeding expenditures undertaken prior to the year
\((t - g - n)\):

\[ G_{t-g-n} = f(E_{t-g-n-1}, \ldots, E_{t-g-n-m}) \]

Current innovations represent additions to the stock of knowledge so that the knowledge
stock evolves over time according to the following formula:

\[ K_t = (1 - \rho)K_{t-1} + I_t \]

where \(0 \leq \rho \leq 1\) is the rate of knowledge depreciation. Here we assume that knowledge
depreciates at the same rate every year. One might argue that this is not a plausible as-
sumption. One would expect the depreciation rate to depend on the state of the technology
and the speed with which new breeding methods replace the old ones. In sectors like canola,
for example, where there is a rapid technological upgrading due to the use of genetic engi-
neering techniques we would expect knowledge to depreciate at a quicker rate over time as
traditional breeding that dominated prior to 1970s is replaced with molecular modification
techniques. In contrast, in the wheat sector where breeding methods have, for the most
part, remained unchanged for decades the assumption of a constant depreciate rate can be
plausible.

By making successive substitutions equation (6.4) yields:

\[ K_{t-1} = K_0 + \sum_{i=0}^{\infty} (1 - \rho)^i I_{t-i} \]

where \( K_0 \) is the initial stock of knowledge and \( I_{t-i} \) is the increment of investment that
adds to the stock of knowledge or flow of knowledge in year \((t - i)\). Thus, knowledge stock
can be represented as an infinite sum of knowledge flows at a point in time. The flow of
knowledge is a function of the average research productivity (the number of ideas generated per researcher), $k$, and the number of researchers, $L^R$. Therefore,

$$I_{t-i} = k_{t-i}L_{t-i}^R$$

(6.6)

The current research productivity, in its turn, depends on the stock of ideas that have already been generated or, in other words, “the state of the art”. “The state of the art” can be represented as a function of past R&D expenditures, where R&D expenditures include both breeding expenditures per se ($E$) and research related to plant physiology, disease resistance and others ($R$). Thus,

$$k_t = f(E_{t-1}, ..., E_{t-1}, R_{t-1}, ..., R_{t-1})$$

(6.7)

Because knowledge stock contains an infinite sum of the knowledge flows at any point of time, it can be written as a function of breeding and research expenditures over an infinite period of time. That is,

$$K_t = f(E_{t-1}, E_{t-2}, ..., R_{t-1}, R_{t-2}, ...)$$

(6.8)

Combining the above equations we can write the output of the breeding program as a function of the breeding expenditures required to produce that output, breeding expenditures incurred in the past breeding programs and past plant-related research effort. If we assume that the outcome of the breeding program is best represented by yield, then the average yield of varieties introduced in year $t$ can be written as:

$$y_t = f(E_{t-g}, ..., E_{t-g-m}, ..., R_{t-g}, ..., R_{t-g-t}, ...)$$

(6.9)

Therefore, the weighted average yield index can also be represented as a function of breeding expenditures and plant related research spending over an infinite number of years. Assuming a linear relationship $Y_t$ can be written:

$$Y_t = \alpha + \sum_{i=0}^{\infty} w_i E_{t-g-i} + \sum_{i=0}^{\infty} b_i R_{t-g-i} + u_t$$

(6.10)

where $w_i$ are the effects attributable to breeding expenditures in year $(t - g - i)$ and $b_i$ are the effects of research expenditures on the yield index. $\sum_{i=0}^{\infty} w_i$ shows the change in the yield index in the long-run as a result of a change in breeding expenditures in one particular year.

In this model the average yield index in year $t$ is a function of breeding expenditures over infinite number of years and specifying it in a finite lag framework would be a significant conceptual error because that would imply imposing a restriction that after some year knowledge depreciates completely. From the econometric estimation point of view truncation of the research lag is analogous to the classic “omitted variable” problem and any truncation of the lag distribution will simply reduce the overall size of the stream of gross and net
benefits, thus producing misleading estimates of rates of return to plant breeding (Alston et al. (2000)). In the following section we will outline the procedure for estimating the infinite lag distribution given in (6.10).


6.1.1. Infinite lag distributions. The equation that we want to estimate is:

\[ Y_t = \alpha + \sum_{i=0}^{\infty} w_i I_{t-1-i} + u_t \]  

where \( \alpha \) and \( w_i \) are unknown constants and \( I_t \) is an exogenous variable independent of the error term \( u_t \).

The distinguishing feature of the model given by 6.11 is that it contains an infinite number of terms and obviously with finite data we cannot estimate the parameters in this equation. If we assume that the conditional mean of \( y_t \) given \( I_t \) is finite so that the sum of the effects of the independent variable is also finite then equation 6.11 can be written as:

\[ Y_t = \alpha + \beta \sum_{i=0}^{\infty} w^*_i I_{t-1-i} + u_t \]

where \( \beta = \sum_{i=0}^{\infty} w_i \) and \( \sum_{i=0}^{\infty} w^*_i = 1 \).

In most of empirical studies the main approach is to approximate the infinite lag structure with finite distributions and assume that the weights, \( w^*_i \), are given by some probability distribution. The most common assumptions employed in empirical studies of rates of return regarding lag structures include inverted-V (Evenson (1967)), polynomial (Almon (1965)) and trapezoidal (Huffman and Evenson (1989, 1992)). However, as was mentioned above truncation of the infinite lag structure is a significant conceptual error and we have to seek for a way to estimate equation 6.12 in its infinite distributed lag form. The general procedure to do this is to assume a specific probability distribution for \( w^*_i \). Since the sum of weights adds to 1 the estimated coefficient \( \beta \) will give a long-run effect of breeding expenditures on the average yield index.

Koyck was one of the first to offer a solution to the estimation of the infinite distributed lag model (Koyck (1954)). It was assumed that the weights follow the geometric distribution:

\[ w^*_i = (1 - \lambda) \lambda^i \]

where \( 0 < \lambda < 1 \) is the parameter capturing the speed of decay in the lag distribution. The higher the value of \( \lambda \) the larger is the effect of the distant expenditures on the current yield index. Substituting the assumed weights into (6.12) and employing the notion of the lag operator yields:
The last term in the above equation follows from the infinite geometric progression rule
$$\sum_{i=0}^{\infty} \lambda^i L^i = \frac{1}{1-10}$$ for $\lambda < 1$.

Applying $1-\lambda L$ to both sides of equation (6.12) we obtain:

$$Y_t = \beta(1-\lambda)Y_{t-1} + \lambda Y_{t-1} + \nu_t$$

where $\nu_t = u_t - \lambda u_{t-1}$.

Some empirical studies estimated equation (6.14) by least squares method, which is computationally feasible since it involves only the available observations for $t = 1, 2, ... T$ and excludes the unobserved part for $t = 0, -1, ... -T$. Unfortunately, however, it is unlikely that application of least squares methods will yield estimators with desirable properties such as consistency. The problem with the above equation is that if $u_t$ are serially independent to start with, the proposed Koicck’s transformation of the infinite lag model yields the model where the regressor, $Y_{t-1}$, is correlated with the error term, $\nu_t$. Thus, OLS estimators of the parameters in (6.14) will be inconsistent. The only instance where this is not so occurs when the error term, $u_t$, obeys the standard first-order Markov scheme with parameter $\lambda$ (Dhrymes (1981)) so that

$$u_t = \frac{2}{1-\lambda} \epsilon_t$$

To overcome the endogeneity problem in equation (6.14) some authors applied instrumental variable estimation. However, the choice of instruments plays a very important role in obtaining “good” estimates and if the chosen instruments are poor then the advantages of instrumental variable (IV) estimation are lost.

Klein (1958) proposed a direct estimation of the infinite distributed lag model and the detailed description of the method is provided in Dhrymes (1981) and Maddala (1977). Before we outline the “direct” method of estimation of (6.12) a few remarks about the geometric lag structure warrant attention. This particular structure has the property that its associated coefficients form a monotone decreasing sequence so that the expenditures in year $(t-1)$ have the maximum impact on $Y_t$ and the impact diminishes over time. This lag structure might not be appropriate for the problem under consideration. We know that the introduced varieties gradually spread out reaching a maximum adoption at some point of time and then their popularity starts declining as pests adapt and new better varieties are released. Thus, we would expect the impact of breeding effort to follow a similar pattern with the initial build up before the decline.
Thus, the geometric lag structure has a desirable property because it allows to model a gradual decline of the effect of past breeding expenditures on the current average yield index, but it lacks the initial phase when the impact builds up. It was noted that the Almon polynomial can capture a build up, however, it cannot be used in the infinite lag framework. Figure 6 depicts the geometric lag structure for $\lambda = 0.9$ and the second order polynomial $\alpha_0 + \alpha_1 i + \alpha_2 i^2 = 0.05 + 0.01i + 0.1i^2$.

Figure 6. The Geometric and Almon lags

Thus, it was suggested that the combination of the two could yield a desirable probability distribution for the lag structure. Schmidt (1974) offered a modification of the Almon Distributed Lag that combines the geometric distribution and Almon polynomial. Speaker, Mitchell and Gelles (1989) considered a class of infinite distributed lag estimators called the geometric combination lags that can be used to estimate both humped and monotonically declining distributions. In our empirical work we will make use of these two approaches.

**Modified Almon Distributed Lag (Schmidt (1974)).** It is assumed that the weights, $w_i$, in

\begin{equation}
Y_t = \alpha + \sum_{i=0}^{\infty} w_i I_{t-i} + u_t
\end{equation}

are specified as follows:

\begin{equation}
w_i = \lambda^i \sum_{j=0}^{p} \gamma_j i^j, 0 \leq \lambda < 1, i = 1, 2, ...
\end{equation}

In equation 6.16 the first member on the right hand side, $\lambda^i$, represents the geometric lag, while $\sum_{j=0}^{p} \gamma_j i^j$ is the Almon polynomial lag with $p$ denoting the order of the polynomial. For example, for the second order polynomial the second part decomposes into $\gamma_0 + \gamma_1 i + \gamma_2 i^2$. 

When $\gamma_1 = \gamma_2 = \ldots = \gamma_p = 0$ the equation is reduced to the geometric lag specification. For small values of $i$ the polynomial portion will dominate and in the latter stages the Koyck (geometric) portion will dominate (Schmidt(1974)), thus making it possible to estimate “humps” in the distribution of the effects of breeding expenditures on the average yield index.

The direct estimation of (6.15) is performed by decomposing the infinite sum into two parts: one that incorporates only the observed sample information and the second that contains the unobserved elements. Thus, we can rewrite (6.15) as

$$Y_t = \alpha + \sum_{i=0}^{t-1} w_i I_{t-i} + \sum_{i=t}^{\infty} w_i I_{t-i} + u_t$$

(6.17)

For illustration purposes we will perform the decomposition for the case when the weights are given by a combination of the second order polynomial and a geometric parameter (Maddala (1977)). So, $w_i = (\gamma_0 + \gamma_1 i + \gamma_2^2) \lambda^i$. Using this specification, (6.17) can be written as

$$Y_t = \alpha + \sum_{i=0}^{t-1} (\gamma_0 + \gamma_1 i + \gamma_2^2) \lambda^i I_{t-i} + \sum_{i=t}^{\infty} (\gamma_0 + \gamma_1 i + \gamma_2^2) \lambda^i I_{t-i} + u_t$$

(6.18)

The first sum on the right-hand side can be written as

$$\gamma_0 z_{0t} + \gamma_1 z_{1t} + \gamma_2 z_{2t}$$

where $z$'s can be generated as follows given the available $T$ observations:

$$z_{0t} = \sum_{i=0}^{t-1} \lambda^i I_{t-i}$$
$$z_{1t} = \sum_{i=0}^{t-1} i \lambda^i I_{t-i}$$
$$z_{2t} = \sum_{i=0}^{t-1} i^2 \lambda^i I_{t-i}$$

Thus, these variables will represent the knowledge stock.

As for the second sum in (6.18), if we denote $j = i - t$ and make the substitution then it becomes

$$\lambda^i \sum_{j=0}^{\infty} (\gamma_0 + \gamma_1 (t+j) + \gamma_2 (t+j)^2) \lambda^j I_{-j} = (\lambda^i) \mu_0 + (t \lambda^i) \mu_1 + (t^2 \lambda^i) \mu_2$$

(6.19)

where

$$\mu_0 = E(Y_0) = \sum_{j=0}^{\infty} (\gamma_0 + \gamma_1 j + \gamma_2 j^2) \lambda^j I_{-j}$$
$$\mu_1 = \sum_{j=0}^{\infty} (\gamma_1 + 2 \gamma_2 j) \lambda^j I_{-j}$$
$$\mu_2 = \sum_{j=0}^{\infty} \gamma_2 \lambda^j I_{-j}$$

Note that $\mu_0, \mu_1$ and $\mu_2$ do not depend at all on the sample observations and are merely a summary characterization of the history of the explanatory variable prior to the sampling
period. These terms are called the truncation remainders or “initial-value parameters” and they are estimated along with the Almon lag parameters $\gamma_0$, $\gamma_1$ and $\gamma_2$.

Thus, the econometric estimation of the model given by (6.18) is performed by constructing $z_{jt}$ variables and estimating the regression equation of the form:

\[
Y_t = \alpha + \gamma_0 z_{0t} + \gamma_1 z_{1t} + \gamma_2 z_{2t} + (\lambda^t)\mu_0 + (t\lambda^t)\mu_1 + (t^2\lambda^t)\mu_2 + u_t
\]

In a general case if we have the Almon polynomial of order $p$ one estimates

\[
Y_t = \alpha + \sum_{j=0}^{p} \gamma_j z_{jt} + \sum_{j=0}^{p} \mu_j (t^j\lambda^t) + u_t
\]

where $Z_{jt} = \sum_{i=0}^{t-1} i^j \lambda^i I_{t-i}$ and $\alpha$, $\gamma_j$ and $\mu_j$ are parameters to be estimated. It should be clear that as the sample size $T$ becomes large, the influence of the terms that reflect the initial conditions, $\lambda^t$, diminishes in importance. For large samples these terms can be omitted, however, it is recommended not to ignore them and keep them in the model.

In the case when there is no contemporaneous effect, that is, when the current expenditures have no impact on the current average yield index and we have one year lag before the effect is realized equation 6.21 is modified as

\[
Y_t = \alpha + \sum_{j=0}^{p} \gamma_j Z_{jt} + \sum_{j=0}^{p} \mu_j ((t - 1)^j\lambda^{t-1}) + u_t
\]

where $Z_{jt} = \sum_{i=0}^{t-2} i^j \lambda^i I_{t-1-i}$

Obviously, to estimate equation 6.21 we have to know the value of $\lambda$ because it enters the equation in a strongly nonlinear fashion making the application of non-linear least squares where $\lambda$ is estimated along with other parameters impossible. The proposed procedure is to perform a grid search over $\lambda$. We know that $0 < \lambda < 1$. So, we can construct the explanatory variables for different values of $\lambda$ and choose that value of $\lambda$ that yields the minimum residual sum of squares. This will give us the maximum-likelihood estimators of $\lambda$, $\gamma$ and $\mu$. The estimators for $\lambda$ and $\gamma$ are consistent and asymptotically efficient but those for $\mu$ are not (Maddala (1977)). But it is $\gamma$ and $\lambda$ that we are interested in to be able to estimate the effect of breeding expenditures on the yield index.

The individual effects of breeding expenditures in year $(t - i)$ on the yield index in year $t$ can be calculated by substituting the estimated coefficients in $w_i = \lambda^i \sum_{j=0}^{p} \gamma_j i^j$. The long run effect can be calculated using the geometric progression rule. For the second order Almon polynomial, for example, the long-run effect is:

\[
\beta = \sum_{i=0}^{\infty} w_i = \sum_{i=0}^{\infty} \gamma_0 \lambda^i + \sum_{i=0}^{\infty} \gamma_1 i \lambda^i + \sum_{i=0}^{\infty} \gamma_2 i^2 \lambda^2
\]
\[ \beta = \frac{\gamma_0}{1 - \lambda} + \frac{\gamma_1 \lambda}{(1 - \lambda)^2} + \frac{\gamma_2 \lambda(1 + \lambda)}{(1 - \lambda)^3} \]

**Geometric combination lags (GCL).** Here it is assumed that the weights are represented by the following class of lag structure:

\[ w_i = \sum_{j=1}^{n} \lambda_j^i = \sum_{j=1}^{n} \gamma_j \left( \frac{j}{n + 1} \right)^i, \quad i = 1, 2, \ldots, \infty \]

Using this weight structure the infinite distributed lag model can be written as:

\[ Y_t = \alpha + \sum_{i=0}^{\infty} \sum_{j=1}^{n} \gamma_j \lambda_j^i I_{t-i} + u_t \]

Rewriting (6.24) so that it contains the expression involving only the observed information and the “initial conditions” expression yields (Speaker, Mitchell and Gelles (1989)):

\[ Y_t = \alpha + \sum_{j=1}^{n} \sum_{i=0}^{t-1} \gamma_j \lambda_j^i I_{t-i} + \sum_{j=1}^{n} \sum_{i=1}^{\infty} \lambda_j^i I_{t-i} + u_t = \sum_{j=1}^{n} \gamma_j Z_{jt} + \sum_{j=1}^{n} \mu_j \lambda_j^i + u_t \]

where

\[ Z_{jt} = \sum_{i=0}^{t-1} \lambda_j^i I_{t-i} \]

\[ \mu_j = \sum_{i=0}^{\infty} \lambda_j^i \gamma_j I_{t-i} \]

are the truncation terms that are estimated along with the other parameters of the model.

To empirically estimate the GCL one should search for the appropriate value of n. Speaker et al. (1989) propose to search for the value of n that minimizes the variance of the regression or choose n by including any \( \lambda_j \) for which the \( Z_j \) has a statistically significant coefficient. The simulation results reported in Speaker et al. (1989) show that an a priori value of \( n = 7 \) or \( n = 8 \) is a good choice for a variety of true lag structures.

The long run effect of breeding efforts on the yield index in the GCL framework can be computed as

\[ \beta = \sum_{j=1}^{n} \frac{\gamma_j (n + 1)}{n + 1 - j} \]

6.1.2. **Time-series properties of data.** So far we have outlined the econometric procedure to directly estimate the infinite distributed lag model. But before undertaking the regression analysis it is important to investigate the properties of the series whenever time-series data are involved.
Many economic series are well modelled as stochastic trends, that is, are non-stationary and integrated of order 1 (I(1) variables). The most common procedure to test for stationarity of the data series is the Augmented Dickey-Fuller (ADF) test, which is known as the test for the unit root in the data.

If we run a regression and find that

$$Y_t = \rho Y_{t-1} + u_t = Y_{t-1} + u_t$$

then we say that the stochastic variable $Y_t$ has a unit root or follows a random walk. A random walk is an example of non-stationary series.

Using this representation of a non-stationary series the Dickey-Fuller test is formulated as follows:

$$\Delta Y_t = \alpha + \delta Y_{t-1} + \alpha_i \sum_{i=1}^{m} \Delta Y_{t-i} + \varepsilon_t$$

(6.27)

where $\Delta Y_{t-i}$ are the “augmented” terms and the idea is to include as many terms so that the residuals in equation 6.27 are serially independent, since the presence of autocorrelation undermines the validity of the ADF test. In empirical studies the number of lagged differences is also chosen on the basis of Akaike (AIC) criteria.

Under the null hypothesis $\delta = 0$, which is equivalent to having a unit root in the series. The critical values for the test have been tabulated by Dickey and Fuller (1979).

It is important to perform the test for unit root because the stochastic properties of the data will have implications with respect to the appropriate statistical methodology. When regressing I(1) variables researchers should be concerned with estimating a spurious regression rather than the “true” relationship between the variables. As Granger and Newbold (1974) an $R^2$ > Durbin-Watson statistics is a good rule of thumb to suspect that the estimated relationship suffers from spurious regression and the estimated results cannot be used to infer about the linkage between the variables.

However, the problem of a spurious regression does not always arise when non-stationary series are involved. To be non-spurious we require that the regression removes the stochastic trend from the dependent variables leaving the stationary residuals. In this case, however, even though the estimated relationship is the true relationship the estimators are super-consistent and we cannot rely on usual inference procedures, that is, the estimated standard errors cannot be used to make inferences about the significance of the coefficients in the model.

Thus, if the regression produces stationary residuals then we have estimated the “genuine” long-run relationship between the series and such series are said to be cointegrated. If this
is the case then differencing of the data to get stationary series would be counterproductive, since it would obscure the long-run relationship between the series (Green (2000)).

The commonly used test for cointegration and also the one employed in this study is the Engle-Granger test. The idea is to test the residuals from the estimated regression for stationarity. This is done by employing the ADF test described earlier. It should be mentioned, however, that the critical values reported by Dickey and Fuller (1979) are not applicable to the cointegration test. The reason for this is that when testing the residuals for stationarity one should take into consideration the fact that the cointegrating vector is estimated rather than given. The critical values will depend on the number of parameters estimated in the cointegration equation and these values have been reported by Davidson and MacKinnon (1993, Table 20.2).

Laybourne and McCabe (1993) noted that the Engle-Granger test for cointegration typically tends to find in favour of the null hypothesis, which is that the residuals are non-stationary, unless there is substantial evidence to the contrary. They proposed an alternative test, which is also applied in this study, that has residual stationarity under the null hypothesis.

The proposed test is performed in the following way. Suppose that the estimated model is

\[ y_t = \alpha_t + x'_t \beta + \epsilon_t \]

where all variables are I(1) and it is assumed that

\[ \epsilon_t \sim I.N.(0, \sigma^2), \alpha_t = \alpha_{t-1} + \nu_t, \alpha_0 = \alpha, \nu_t \sim I.N.(0, \sigma^2 \nu^2) \]

The null hypothesis for the cointegration test is that \( \sigma^2_\nu = 0 \) (against the alternative that it is positive). If the intercept is constant, so that its variance is zero, then the series are cointegrated. That is the linear combination given in (6.28) yields a stationary residual.

The test statistic for the test is

\[ t - \text{stat} = T^{-2} s^{-2}_e e' V e \]

where \( T \) is the sample size, \( s^2_e = \frac{e'e}{T} \), \( e \) denotes the estimated residuals from the cointegrating regression (6.28) and \( V \) is a \( T \times T \) matrix whose \( ij \)th element is equal to the minimum of \( i \) and \( j \), \( i, j = 1, ..., T \).

Sephton (1996) performed Monte-Carlo simulations to derive the critical values for the Laybourne and McCabe cointegration test and reported these values for different sample sizes and different number of variables in the cointegrating vector.

6.2. Description of the data.
6.2.1. Wheat breeding effort. In Canada wheat breeding is performed by Agriculture and Agri-Food Canada (AAFC) research centers located in Winnipeg, Swift Current, Lethbridge, Lacombe, Beaverlodge and Ottawa as well as at the University of Saskatchewan, University of Alberta, University of Manitoba and University of Guelph. In this study we are focusing on wheat breeding in Western Canada and the breeding effort of the AAFC research center in Ottawa and the University of Guelph is excluded from the analysis.

The research effort is tracked by the Canadian Agricultural Research Council that maintains the database of research projects submitted by different research agencies. This database is called an Inventory of Canadian Agri-Food Research (ICAR). ICAR database provides information on the number of professional person years devoted to a particular project as well as technical person years. In the proposal submitted by the AAFC to the Western Grain Research Foundation (WGRF) it was indicated that in 1994/95 for research centers within AAFC the average rate for the technical person year accounted for 35% of that for professionals. Assuming that labor is paid its marginal product we can infer that the productivity of technical staff corresponds to 35% of that of professionals. Thus, the technical person years can be converted to professional person years using the coefficient of 0.35.

To get the data on wheat breeding effort in Western Canada ICAR database was searched for wheat breeding research projects undertaken by research stations and universities in Western Canada over the thirty-year period 1977-2006. For the purposes of this study wheat breeding was defined to include projects related to the development of new wheat varieties, wheat genetics and wheat variety assessment. Wheat genetics category included development of genetic markers, cytogenetic studies in wheat, genetic and physiological studies of wheat resistance to pests, deceases, drought and colds. The decision to include a particular project into the wheat breeding category was made based upon the direct involvement of wheat breeders in that project. The list of wheat breeders over 1977-2006 was compiled with a help of the wheat breeders currently involved in wheat breeding who provided information on their predecessors.

It should be mentioned that since reporting projects is not compulsory there maybe an error due to underreporting. It seems that in recent years (2002-2006) it has become more of a problem. We tried to “correct” for the projects not reported by the breeders. For example, no projects were reported by the University of Manitoba after 2002 but we do know that there is one wheat breeder who is currently involved full-time in wheat breeding. Thus, we added one professional person year for each year from 2002. The situation with the University of Alberta is analogous: one wheat breeder has been involved since 2001 but no projects were reported. So, we added one professional person year for the University of Alberta over 2001-2006. No projects were reported by Robert Graf, a winter wheat breeder...
from AAFC in Lethbridge, after 2003. Based on the knowledge that he’s been full-time breeder over these years we added one professional person year to the breeding effort at AAFC research center in Lethbridge over 2004-2006.

The wheat breeding effort in Western Canada expressed in terms of professional and technical person years is shown in Figure 7.

![Figure 7. Wheat breeding in Western Canada in 1977-2006](image)

There are a few caveats about the data we should be aware of. Although the search was limited to projects classified as *wheat* breeding/genetics, some of the projects also include other cereals such as barley. Some of the projects are only partially related to wheat breeding while some portion of them may be on, say, pathology. Since we had no direct reports that would help us calculate just the wheat breeding component we used the person years reported in those projects as “wheat breeding” even if the project was not entirely on wheat breeding per se.

In order to estimate the rates of return to wheat breeding all classes of wheat, excluding durum wheat, have been pooled. This was dictated, first and foremost, by the data. Prior to 1995 the projects were classified as related to common wheat, durum or other, from 1996 the code became spring, winter, durum and other wheat. Thus, in many cases the projects from the ICAR database could not be attributed to a particular class of wheat.

The data on wheat breeding expenditures expressed in monetary terms were compiled from two sources. For 1977-1991 we employed the data reported in Klein, Freeze and Walburger
(1996). Their data were converted to nominal values using the Consumer Price Index (CPI) (1991=100) and the nominal values were then converted to 2006 dollars using CPI. Breeding expenditures over 1994-2006 were calculated as follows. Every five years the AAFC and the universities conducting wheat breeding research submit the proposals to the WGRF to obtain the funds (wheat check-off funds). These reports contain information on the current breeding activities as well as 5 year projections of wheat breeding expenditures. Information on the amount of resources (check-off and royalties) provided by the WGRF to AAFC research centers in Winnipeg, Lethbridge and Swift Current as well as the University of Saskatchewan and the University of Manitoba was obtained from the WGRF financial statements. Of the resources provided to the AAFC 21% goes to the development of durum wheat, thus only 79% of the WGRF funding was used for bread wheat development. At the University of Saskatchewan, 25% of the WGRF funding is devoted to Canadian Western Amber Durum programs. According to the conversation with Pierre Hucl, a spring wheat breeder at the University of Saskatchewan, the WGRF funds account for about 25% of the total cost of the wheat breeding program. For the AAFC the WGRF funds are estimated to be about 30% of total wheat breeding expenditures (including overhead). Using this information we calculated the bread wheat breeding expenditures at the AAFC research centers in Winnipeg, Swift Current and Lethbridge and the University of Saskatchewan. By diving these numbers by the number of professional person years (PPY) at these research centers compiled from ICAR we got an estimate of the cost of one professional person year. These estimates were then applied to the breeding effort in terms of PPY at AAFC branch in Lacombe, at the University of Manitoba and the University of Alberta. The data for 1992-1994 were extrapolated using the four degree polynomial: the estimated equation for prediction was $Y_t = 888.68 + 582.65t - 87.54t^2 + 5.72t^3 - 0.11t^4$, where $t$ is a time trend. Nominal values were then converted into real terms using CPI (2006=100). The wheat breeding expenditures are presented in Figure 8.

The data show that over 1977-2001 the wheat breeding expenditures remained relatively stable and started to increase after 1995. Such an increase is not observed for breeding expenditures expressed in person years, though. Thus, there might be some inconsistency between the two sources of data on wheat breeding expenditures: Klein et al. (1996) and the WGRF reports. But because we don’t have a common year for these two sources we cannot check how big the discrepancy in the data is. In the econometric estimation below we will be using the professional person years as an independent variable rather than monetary expenditures, since we believe that this is a better and more reliable estimate of the breeding effort in Western Canada.
In order to calculate the rates of return to wheat breeding we are econometrically estimating the relationship between yields and wheat breeding expenditures. The procedure to construct the average yield index began by converting the relative yield index of different wheat varieties to the same base variety - Manitou.

The yield index for 1977-1998 was taken from Gray and Malla (2000). The report contains a detailed description of the data sources used to construct the yield index. Following the same procedure we updated the yield index data up to 2006.

The data on relative yield indexes for different varieties were taken from “Varieties of grain crops in Saskatchewan” reports published by Saskatchewan Agriculture and Food. Since this information was not available from other provinces Saskatchewan trial yields were used as a national proxy. The data on the percentage of acreage of each variety after 1998 were taken from the Canadian Wheat Board variety surveys.

Several aspects about yield data are worth mentioning. First, we are using experimental rather than industry (farm) data and it is well recognized that the experimental yields overestimate farm level yields (Zentner, Peterson (1984)). However, we expect that the use of the relative yield index rather than absolute yield levels eliminates the problem as it may not be unreasonable to expect the same relative performance of the varieties in farmers’ fields.
The second aspect relates to the consideration of only yield effects. By focusing only on yield, we are ignoring some important characteristics of the varieties such as protein level, days to maturity, solid stems to resist sawfly and others. For example, solid-stemmed varieties yield a bit less than hollow-stemmed varieties but they have enough resistance to reduce the sawfly damage by over 50%\(^2\). Ignoring these non-yield characteristics is likely to bias the estimated benefits downward.

The third aspect relates to pooling all bread wheat classes together. It is well recognized that different classes have different quality profiles. For example, CPS wheats are 15-20% higher yielding than CWRS wheats with protein level 1-1.5% units lower. It should be mentioned, however, that even though CPS has lower protein content it has some other characteristics lacking in CWRS wheats that make it suitable for a particular market. For each class of wheat there are some special characteristics buyers are seeking and willing to pay for and their importance is reflected in the area sown under each class of wheat. Thus, by weighting by the seeded acreage when constructing the “pooled” yield index we are kind of weighting by the importance of quality characteristics inherent to each wheat class.

The calculated annual wheat yield index is shown in Figure 9.

![Figure 9. Average Weighted Bread Wheat Yield Index](image-url)

6.2.3. *Quantity, price data, CPI.* The data on quantity of wheat produced in Prairie provinces were obtained from Statistics Canada, CANSIM database, Table 001-0010. The source of

farm wheat price was Saskatchewan Agriculture and Food\textsuperscript{3}. The farm price in Saskatchewan has been used as a farm price for Prairie provinces because it is the wheat production center. The CPI was obtained from Statistics Canada, CANSIM database, Table 326-0002.

To calculate the Canada’s share in world production we used the USDA data on world wheat production. The source of the data on domestic wheat use was “Grains and Oilseeds Outlook” published by Agriculture and Agri-Food Canada.

6.3. Econometric analysis: results and discussion. The general form of the model we are going to estimate is

\begin{equation}
Y_t = \alpha + \sum_{i=0}^{\infty} w_i I_{t-i} + u_t
\end{equation}

A few notes about the exact specification of the model are in place. An inclusion of the intercept term \( \alpha \) is important in this model because it has a special meaning: \( \alpha \) shows what yield index would have been had there been no wheat breeding industry in Canada at all. Usually little attention is paid to the intercept and in similar studies it is very often omitted from the model. Omitting the intercept from the model would be a specification error since it would imply that without breeding effort yield index would be zero. This seems implausible because even before the breeding industry was established in Canada, wheat had been grown in Canada with wheat varieties brought from different countries. It may not be unreasonable to restrict the coefficient to 100. If Canada had not had its own wheat breeding sector then varieties similar to the base variety Manitou would have been brought from, say, the US. Since wheat is a locally adapted plant, varieties developed in the US would not have performed in Canada as good as they did in the US but it is reasonable to assume that they would have performed as good as the base variety registered in Canada in 1965. Thus, the estimated model is:

\begin{equation}
Y_t = 100 + \sum_{i=0}^{\infty} w_i I_{t-i} + u_t
\end{equation}

Time series properties of the data. In this section we are going to present the results from the Modified Almon Distributed Lag (MADL) and Geometric Combination Lag (GCL) models. The first step in the modelling approach is to examine the time series properties of the individual data series.

In the MADL model we combine the geometric structure with the polynomial of the degree two. Thus, we have constructed three ’knowledge stock’ variables, \( Z_{0t} \), \( Z_{1t} \) and \( Z_{2t} \), specified in equation 6.18 and the “initial conditions” variables. For the GCL model we have tried

\textsuperscript{3}Price reports are available on-line: http://www.agriculture.gov.sk.ca/Default.aspx?DN=02dce904-ef01-4e82-b31c-816c7b2f29a3
Table 2. *Augmented Dickey-Fuller test results for levels and differences*

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<tr>
<td>ΔZ_0</td>
<td>Cannot accept at 10%</td>
<td>0</td>
<td>-3.27</td>
<td>-4.34 -3.59 -3.23</td>
</tr>
<tr>
<td>ΔZ_1</td>
<td>Cannot accept at 1%</td>
<td>1</td>
<td>-4.63</td>
<td>-4.36 -3.59 -3.23</td>
</tr>
<tr>
<td>ΔZ_2</td>
<td>Cannot accept at 10%</td>
<td>2</td>
<td>-2.92</td>
<td>-3.69 -2.98 -2.63</td>
</tr>
<tr>
<td>ΔZ_1^{GCL}</td>
<td>Cannot accept at 1%</td>
<td>0</td>
<td>-5.21</td>
<td>-3.69 -2.98 -2.63</td>
</tr>
<tr>
<td>ΔZ_2^{GCL}</td>
<td>Cannot accept at 1%</td>
<td>0</td>
<td>-4.28</td>
<td>-3.69 -2.98 -2.63</td>
</tr>
<tr>
<td>ΔZ_3^{GCL}</td>
<td>Cannot accept at 5%</td>
<td>0</td>
<td>-3.37</td>
<td>-3.69 -2.98 -2.63</td>
</tr>
<tr>
<td>ΔZ_4^{GCL}</td>
<td>Cannot accept at 10%</td>
<td>0</td>
<td>-3.42</td>
<td>-4.34 -3.59 -3.23</td>
</tr>
</tbody>
</table>

For $n = 1, 2, ..., 6$. Based on the Akaike information criterion (AIC) $n = 4$ was chosen. So, four stock variables $Z_1^{GCL}, ..., Z_4^{GCL}$ and four “initial conditions” variables have been constructed.

To study the time series properties of the dependent and explanatory variables we performed the standard Augmented Dickey-Fuller test in both levels and first differences. The number of the augmented terms was chosen to minimize the AIC. The results are reported in Table 2.

We fail to reject the hypothesis of a unit root for all variables in levels. However, all the variables reject the null hypothesis of a unit root at 10% level of significance in first differences. Thus, we can conclude that all of the variables are I(1) in levels.

As was mentioned in the previous section first differencing of the data prior to running the regression will remove the nonstationarity problem but with a loss of a long-run relationship between the variables if it exists. Thus, for a moment we will ignore the time-series properties of the data and run the regression in levels. But we will perform the cointegration test to make sure that the estimated relationship is genuine rather than spurious due to stochastic trends in the data.

*Estimated Modified Almon Distributed Lag and Geometric Combination Lag models.*

In the MADL model we are employing the polynomial of degree two. Thus, the weights are given by

$$w_i = (\gamma_0 + \gamma_1 i + \gamma_2 i^2)\lambda^i$$
We performed a grid search over $0 < \lambda < 1$ and the optimum value was chosen on the basis of minimum residual sum of squares. We first varied $\lambda$ at intervals of 0.1 and then at intervals of 0.01 in the second round. The sum of squared residuals was minimized for $\lambda = 0.83$. The AIC was used to choose the gestation lag and it was minimized for the gestation lag of three years. That is, breeding expenditures in years $(t - 1), (t - 2)$ and $(t - 3)$ have no impact on the yield index in year $t$. Thus, the estimated relationship is:

\[
(6.32) \quad Y_t = 100 + \sum_{i=0}^{\infty} w_i I_{t-3-i} + u_t
\]

where $I$ is measured in professional person years devoted to wheat breeding and $Y_t$ is the area weighted yield index.

In estimating the GCL model we tried the values for $n$ from one to six. The variance of the regression was minimized for $n = 4$. The AIC was minimized for the model with 5 year gestation lag, which means that investment made in year $(t - 5)$ starts affecting the yield index in year $t$. Therefore, the estimated relation is:

\[
(6.33) \quad Y_t = 100 + \sum_{i=0}^{\infty} w_i I_{t-5-i} + u_t
\]

The estimation results are provided in Table 3.
The estimated long-run effect from the MADL model is 0.69, which means that adding one professional in one year increases wheat yield index by 0.69 points. It’s worth noting that this effect is not instantaneous: it starts 3 years after the investment and it takes many years to have this effect realized. Because the model assumes the depreciation of the ‘useful’ knowledge stock the contribution of the additional person year will fade away eventually and approach zero as we increase the time length. The estimated weights are shown in Figure 10. As can be seen from the figure the impact first builds up and it reaches a peak 13 years after the expenditures have been incurred (10 years plus 3 year gestation lag) and then the contribution of the additional professional starts declining but even after 50 years knowledge created by one professional scientist contributes to the development of new improved varieties. An important description of the model is the mean lag. The mean lag gives information on the mean length of time it takes for a change in the determining variable (wheat breeding expenditures) to be transmitted to the dependent variable (yield index). The mean lag can be calculated as \( m = \sum_{i=0}^{\infty} iw_i \) and in our case it is 10 years.

![Figure 10. The impact of adding one professional person year on the wheat yield index: the weights from the MADL model](image)

The estimated long-run effect from the GCL model is a bit lower - 0.61. The estimated weights are shown in Figure 11. As can be seen from the figure the effect of breeding expenditures in year \( t - 7 \) (including 5 year gestation period) on the yield index is negative and then it starts building up. The estimated weights indicate that the maximum impact is reached in the eleventh year after adding one professional person year (including 5 year gestation lag) and its contribution to the development of new varieties starts declining afterwards. It should be mentioned that the GCL model seems to be sensitive to the choice of
even though the marginal impact of wheat breeding on yield index is about the same for different specifications the weights structure varies substantially. We chose the specification that minimized the variance of the regression.

Figure 11. The impact of adding one professional person year on the wheat yield index: the weights from the GCL model

A few remarks about the estimates presented in Table 3 should be made. First, almost all of the estimated coefficients are insignificant and one would be inclined to infer that wheat breeding expenditures don’t have a statistically significant impact on the yield index. At the same time the F-statistics for the joint test of coefficient significance is highly significant and we cannot accept the hypothesis that all the coefficients are zero at 1%. This observation combined with the high value of R-square is an indicative of multicollinearity problem. Given the way the “knowledge stock” variables are created multicollinearity is not unlikely, in which case the estimated coefficients are still consistent (except for the coefficients on the “initial conditions” variables, which are of no primary interest to us) and unbiased but inefficient. Furthermore, if the variables are cointegrated and if what we have estimated is a genuine long-run relationship between nonstationary variables then the estimates are superconsistent and the usual inference procedures cannot be applied. As was mentioned in the previous section an indicative of a spurious regression is the value of the Durbin-Watson statistics exceeding the R-squared, which is not the case for the estimated regressions. Thus, there are reasons to suspect that the estimated standard errors are superconsistent and cannot be relied upon to make inferences about statistical significance of the coefficients, though below we will perform the formal testing for cointegration.
Table 4. Cointegration test results

<table>
<thead>
<tr>
<th>Decision rule</th>
<th>Test statistics</th>
<th>Critical values(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(1%)</td>
</tr>
<tr>
<td><strong>Engle and Granger test</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MADL</td>
<td>Cannot accept (H_0) of a unit root</td>
<td>-5.75</td>
</tr>
<tr>
<td><strong>Laybourne and McCabe test</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MADL</td>
<td>Fail to reject (H_0) of stationary residuals at 10% sign. level</td>
<td>0.029</td>
</tr>
<tr>
<td>GCL</td>
<td>Fail to reject (H_0) of stationary residuals at 10% sign. level</td>
<td>0.014</td>
</tr>
</tbody>
</table>

\(^1\) Critical values for the Engle and Granger cointegration test are taken from Davidson and MacKinnon (1993, Table 20.2)

Critical values for the Laybourne and McCabe (1993) cointegration test are taken from Sephton (1996)

Cointegration analysis. To test for the existence of a long-run relationship between the variables we have employed the two tests described above. The results are presented in Table 4. Because Davidson and MacKinnon (1993, Table 20.2) provide the critical value only for six variables at most we cannot apply this test to the GCL model where we have eight variables.

The results of the cointegration tests suggest that the residuals from both models are stationary: the series are cointegrated and there exists a long-run relationship between the area weighted yield index and knowledge stock, which we have estimated. Therefore, we conclude that the estimated relationships are not spurious regressions but genuine relationships between the variables. Given this, the estimators are superconsistent and the usual inference procedure cannot be applied.

6.4. The returns to wheat breeding. The returns to wheat breeding are calculated from a Canadian perspective. It is assumed that the increase in wheat yield provides additional revenue to the producer at no additional cost. One possible way to calculate the rates of return is to assume that the profits beyond the farm price are not affected by wheat yield increases and that the prevailing prices would not be influenced by the changes in yield (Gray and Malla (2000)). This is a small open economy assumption. In this case the benefits to wheat breeding in year \(t\) can be calculated as

\[
B_t = AP_tQ_t
\]

where \(A = \frac{\Delta Y_t}{Y_t}\) is the proportional change in yield due to wheat breeding research, \(P_t\) - is the (world) wheat price and \(Q_t\) is the quantity of wheat produced in Western Canada.
The present value of benefits can be calculated as

\[
PV(B) = \sum_{i=0}^{\infty} \frac{A_{t+i}P_{t+i}Q_{t+i}}{(1 + r)^i}
\]

One might argue, however, that the change in Canadian production will leave the world price unaffected. Even though Canada’s share in total world production accounts for approximately 5% it is the sixth largest wheat producer and the second largest exporter of wheat. Thus, in this study we also calculate the benefits from wheat breeding under the assumption that Canada is an open economy with the wheat demand curve not perfectly elastic. For this purpose we use the producer-consumer surplus framework. The basic model is shown in Figure 12.

**Figure 12.** Benefits from wheat breeding research

In this figure $S_0$ is the initial wheat supply curve. Wheat breeding enhances yields, which shifts the supply curve outwards to $S_1$. The shift in the supply curve given a proportional change in yield $A$ can be found as follows. If the production costs per acre are $C$ and wheat yields $Y$ tons per acre, then the marginal cost per ton would be $\frac{C}{Y}$. Assuming that the yield increase does not bring about additional costs, the new marginal cost is $\frac{C}{Y(1+A)}$. Thus, the proportional shift in the supply curve can be calculated as $\frac{A}{Y(1+A)}$.

In Figure 12 $D_T$ denotes the total demand for wheat, which is domestic consumption plus foreign demand. $D_D$ is the domestic consumption of wheat. The elasticity of the total wheat demand is closely related to the elasticity of the world demand, which is assumed to be 0.15. To see this write the elasticity of total wheat demand in Canada as
\( \varepsilon^C = \frac{\Delta Q^C P^C}{Q^C \Delta P^C} \)

and the world elasticity

\( \varepsilon^W = \frac{\Delta Q^W P^W}{Q^W \Delta P^W} \)

Since Canada is an open economy the world wheat price will prevail on the Canadian market. Thus, the change in Canadian price will be the same as the change in the world price. That is, \( \frac{P^C}{\Delta P^C} = \frac{P^W}{\Delta P^W} \). Furthermore, under the assumption that the change in the world supply comes solely from the expansion in Canadian production, the proportional change in the world supply can be rewritten as

\( \frac{\Delta Q^W}{Q^W} = \frac{\Delta Q^C}{Q^C} \frac{Q^C}{Q^W} = \frac{\Delta Q^C s^C}{Q^C} \)

where \( s^C \) is the share of Canada in total world wheat production.

Substituting (6.38) into (6.37) and using the equation for the elasticity of Canadian demand yields

\( \varepsilon^W = \varepsilon^C s^C \)

or, equivalently, \( \varepsilon^C = \frac{\varepsilon^W}{s^C} \). Thus, the elasticity of the total demand curve \( D_T \) is the ratio of the world demand elasticity to the Canada’s share in production. Given this elasticity and the elasticity of wheat supply in Canada we can calculate the change in production in Canada due to the supply curve shift and the change in the world price for wheat.

Given the parallel shift in supply and the change in the wheat price the change in the producer surplus is represented by \( dP_{ce} \). In calculating the change in the consumer surplus only the domestic consumption matters. At a price \( P_0 \) \( Q^D_0 \) was consumed domestically. Domestic demand increases to \( Q^D_1 \) as the price goes down to \( P_1 \). The change in the domestic consumer surplus is the area \( P_1 P_0 ab \). These effects can be expressed algebraically as follows (Alston, Norton and Pardey (1995, p. 210):

\( \Delta PS = P_0 Q_0 (K - Z) (1 + 0.5Z\varepsilon^C) \)

\( \Delta CS = Q^D_0 Z (1 + 0.5Z\varepsilon^D) \)

where \( P_0 \) is the factual price observed in Canada, \( Q_0 \) is the factual wheat production, \( Q^D_0 \) is the domestic consumption, \( K = \frac{A}{A+\Delta A} = \frac{\Delta Y}{Y+\Delta Y} \) is the proportional shift in the supply curve,
\( \varepsilon^C = \frac{\varepsilon^W}{\varepsilon^D} \) is the absolute value of the elasticity of the Canadian total wheat demand, \( \varepsilon^C_D \) is the elasticity of the Canadian domestic demand, \( \eta \) is the elasticity of supply, \( Z = \frac{K\eta}{(\eta + \varepsilon^C)} \) is the proportional reduction in the wheat (world) price.

After calculating the benefits and costs of wheat breeding research one can find the internal rate of return (IIR), \( r \), by solving

\[
\sum_{i=0}^{\infty} \frac{B_{t+i}}{(1+r)^i} - \sum_{i=0}^{\infty} \frac{C_{t+i}}{(1+r)^i} = 0
\]

To calculate the marginal rate of return we are considering two scenarios. In scenario 1 one professional scientist is added in 2005. Thus, in the factual scenario wheat breeding expenditures are the observed professional person years over 1977-2005, while in the counterfactual in 2005 the number of PPyPs devoted to wheat breeding is increased from 23.96 to 24.96. In scenario 2 one professional person year is added to each year from 1977 to 2005. The annual future wheat breeding expenditures (over 2007-2096 years) are assumed to remain at the 2006 level, which is 24 professional person years. For the calculation of the benefits, it is assumed that in the future the real wheat price stays at the 2006 level and Canada’s share in total world wheat production is \( 4.8\% \) over 2007-2096 (which is the average of Canada’s share throughout 1980-2006).

We used the estimated models presented above to calculate the benefits from wheat breeding. The factual person years were used to predict the factual yields, while the counterfactual person years were used to predict the counterfactual yields. The difference between the two gives research induced yield change. When one professional is added in 2005 the marginal contribution to the yield will be that presented in Figure 10 and 11 for the MADL and GCL model, respectively. The calculated marginal rate of return for scenario 1 is shown in Table 5.

The second column in Table 5 gives the marginal rate of return to a professional scientist when the cost of one PPy in real terms is 397.06 thd. dollars (calculated based on the WGRF reports). The third column gives an estimate of the marginal rate of return when we assume that the real cost of one PPy in 2005 was 500 thd. dollars, which is likely to be an overestimate of the cost of a professional involved in wheat breeding. As can be seen from the table the marginal rates of return to wheat breeding are rather high. The MADL model produces a higher estimate of IIR and it is in the 43-53% range depending on the cost of one PPy in 2005. The results do not differ much when we assume (i) that Canada is a small open economy, and (ii) when we assume that an increase in wheat yield in Canada may affect the world price. The marginal rates of return do not seem to be very sensitive to the assumptions about the elasticity of Canadian wheat supply and the elasticity of the Canadian domestic demand. The IIR from the GCL are somewhat lower but they are, nevertheless,
Table 5. Scenario 1 IRR: one additional professional scientist added in the year 2005

<table>
<thead>
<tr>
<th>Based on econometric results from</th>
<th>IRR(^1)</th>
<th>IRR(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modified Almon Distributed Lag model</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Under the assumption of a perfectly elastic demand curve(^3)</td>
<td>51%</td>
<td>45%</td>
</tr>
<tr>
<td>Under the assumption that (\epsilon^c = \frac{\epsilon^w}{\epsilon^p}):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\eta = 0.2)</td>
<td>(\epsilon_B^c = -0.1)</td>
<td>53%</td>
</tr>
<tr>
<td>(\eta = 0.6)</td>
<td>(\epsilon_B^c = -0.1)</td>
<td>51%</td>
</tr>
<tr>
<td>(\eta = 1.0)</td>
<td>(\epsilon_B^c = -0.1)</td>
<td>50%</td>
</tr>
<tr>
<td>(\eta = 1.5)</td>
<td>(\epsilon_B^c = -0.1)</td>
<td>49%</td>
</tr>
<tr>
<td>(\eta = 0.2)</td>
<td>(\epsilon_B^c = -1.0)</td>
<td>53%</td>
</tr>
<tr>
<td>(\eta = 0.6)</td>
<td>(\epsilon_B^c = -1.0)</td>
<td>51%</td>
</tr>
<tr>
<td>(\eta = 1.0)</td>
<td>(\epsilon_B^c = -1.0)</td>
<td>50%</td>
</tr>
<tr>
<td>(\eta = 1.5)</td>
<td>(\epsilon_B^c = -1.0)</td>
<td>49%</td>
</tr>
<tr>
<td><strong>Geometric Combination Lag model</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Under the assumption of a perfectly elastic demand curve</td>
<td>39%</td>
<td>35%</td>
</tr>
<tr>
<td>Under the assumption that (\epsilon^c = \frac{\epsilon^w}{\epsilon^p}):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\eta = 0.2)</td>
<td>(\epsilon_B^c = -0.1)</td>
<td>41%</td>
</tr>
<tr>
<td>(\eta = 0.6)</td>
<td>(\epsilon_B^c = -0.1)</td>
<td>40%</td>
</tr>
<tr>
<td>(\eta = 1.0)</td>
<td>(\epsilon_B^c = -0.1)</td>
<td>39%</td>
</tr>
<tr>
<td>(\eta = 1.5)</td>
<td>(\epsilon_B^c = -0.1)</td>
<td>38%</td>
</tr>
<tr>
<td>(\eta = 0.2)</td>
<td>(\epsilon_B^c = -1.0)</td>
<td>41%</td>
</tr>
<tr>
<td>(\eta = 0.6)</td>
<td>(\epsilon_B^c = -1.0)</td>
<td>40%</td>
</tr>
<tr>
<td>(\eta = 1.0)</td>
<td>(\epsilon_B^c = -1.0)</td>
<td>39%</td>
</tr>
<tr>
<td>(\eta = 1.5)</td>
<td>(\epsilon_B^c = -1.0)</td>
<td>38%</td>
</tr>
</tbody>
</table>

\(^1\) - when the collected data on wheat breeding are used: 1977-1991 Klein et al. (1996), 1995-2006 – based on WGRF reports

\(^2\) - when we assume that the real spending per professional scientist remained constant over 1977-2006 at the level of 500 thd. 2006 dollars

\(^3\) - This is equivalent to assuming that Canada is a small open economy

high: ranging from 35 to 43% depending on the elasticity of wheat supply in Canada and the cost of one professional scientist. It should be mentioned that these calculations are based on the assumption that the real price of wheat will remain at the TRRY in the future. Given the current developments on the world wheat market with the wheat price rapidly increasing due to higher demand and low world wheat stocks it is not unlikely to expect an increase in the real wheat price, which would produce even higher marginal rate of return to wheat breeding.

The second scenario considered in this study describes the benefits that would have been realized if one professional person year had been added to each year over 1977-2005. The results are reported in Tables 6 and 7.

As can be seen from Table 6 adding one professional scientist to each year over 1977-2005 on average could have generated 4.8 mln. dollars in net benefits annually. The effect of
### Table 6. Benefits from adding one professional scientist to each year over 1977-2005

<table>
<thead>
<tr>
<th>Year</th>
<th>Proportional change in yield</th>
<th>Benefits(^1), thd. 2006 dollars</th>
<th>Costs, 2006 dollars per PPY</th>
<th>Present value of net benefits(^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MADL(^1)</td>
<td>GCL(^1)</td>
<td>MADL</td>
<td>GCL</td>
</tr>
<tr>
<td>1977</td>
<td>250</td>
<td>-250</td>
<td>-250</td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>243</td>
<td>-232</td>
<td>-232</td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>222</td>
<td>-202</td>
<td>-202</td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td>1042</td>
<td>216</td>
<td>714</td>
<td>-186</td>
</tr>
<tr>
<td>1981</td>
<td>2197</td>
<td>214</td>
<td>1631</td>
<td>-176</td>
</tr>
<tr>
<td>1982</td>
<td>3405</td>
<td>236</td>
<td>2833</td>
<td>458</td>
</tr>
<tr>
<td>1983</td>
<td>4724</td>
<td>23</td>
<td>3374</td>
<td>759</td>
</tr>
<tr>
<td>1984</td>
<td>4736</td>
<td>-688</td>
<td>248</td>
<td>3199</td>
</tr>
<tr>
<td>1985</td>
<td>6001</td>
<td>298</td>
<td>3871</td>
<td>11</td>
</tr>
<tr>
<td>1986</td>
<td>7365</td>
<td>216</td>
<td>4608</td>
<td>1747</td>
</tr>
<tr>
<td>1987</td>
<td>7119</td>
<td>177</td>
<td>4262</td>
<td>3004</td>
</tr>
<tr>
<td>1988</td>
<td>7182</td>
<td>164</td>
<td>4103</td>
<td>3858</td>
</tr>
<tr>
<td>1989</td>
<td>10636</td>
<td>179</td>
<td>5823</td>
<td>6357</td>
</tr>
<tr>
<td>1990</td>
<td>12297</td>
<td>171</td>
<td>6431</td>
<td>7598</td>
</tr>
<tr>
<td>1991</td>
<td>13101</td>
<td>166</td>
<td>6533</td>
<td>7985</td>
</tr>
<tr>
<td>1992</td>
<td>15806</td>
<td>177</td>
<td>7518</td>
<td>9288</td>
</tr>
<tr>
<td>1993</td>
<td>16692</td>
<td>172</td>
<td>7269</td>
<td>8974</td>
</tr>
<tr>
<td>1994</td>
<td>15057</td>
<td>192</td>
<td>6485</td>
<td>7920</td>
</tr>
<tr>
<td>1995</td>
<td>23590</td>
<td>225</td>
<td>9708</td>
<td>11623</td>
</tr>
<tr>
<td>1996</td>
<td>25963</td>
<td>271</td>
<td>10167</td>
<td>11904</td>
</tr>
<tr>
<td>1997</td>
<td>19600</td>
<td>265</td>
<td>7287</td>
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</tr>
<tr>
<td>1998</td>
<td>17440</td>
<td>276</td>
<td>6161</td>
<td>6889</td>
</tr>
<tr>
<td>1999</td>
<td>20375</td>
<td>290</td>
<td>6666</td>
<td>7525</td>
</tr>
<tr>
<td>2000</td>
<td>19779</td>
<td>284</td>
<td>6347</td>
<td>6805</td>
</tr>
<tr>
<td>2001</td>
<td>18516</td>
<td>311</td>
<td>5645</td>
<td>5945</td>
</tr>
<tr>
<td>2002</td>
<td>14291</td>
<td>342</td>
<td>4119</td>
<td>4253</td>
</tr>
<tr>
<td>2003</td>
<td>18902</td>
<td>341</td>
<td>5220</td>
<td>5275</td>
</tr>
<tr>
<td>2004</td>
<td>20066</td>
<td>405</td>
<td>5266</td>
<td>5245</td>
</tr>
<tr>
<td>2005</td>
<td>18945</td>
<td>397</td>
<td>4591</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>20011</td>
<td>4775</td>
<td>4639</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>13484</td>
<td>247</td>
<td>4795</td>
<td>4778</td>
</tr>
</tbody>
</table>

\(^1\) – MADL model incorporates a 3 year gestation lag. Thus, the effect from adding one PPY to each year over 1977-2005 starts showing in 1980

\(^2\) – GCL model incorporates a 5 year gestation lag. Thus, the effect from adding one PPY to each year over 1977-2005 starts showing in 1982

\(^3\) – Assuming a perfectly elastic total wheat demand in Canada

\(^4\) – Assuming the real discount rate of 5%

Adding a professional is far more reaching, however, and it will have repercussions far beyond the year 2006.

As can be seen from Table 7 the internal rates of return to a professional scientist are very high. We believe that the wheat breeding data we have at hand is an underestimate of the real wheat breeding expenditures while 500 thd. dollars per PPY is an overestimate. Thus, the results from MADL model show that IRR will be somewhere in the 64-109% range depending on the cost of one professional person year involved in wheat breeding. GCL model produces estimates of IRR in the 44-71% range, which is still a very high number. The marginal internal rate of return over the 1977-2006 period is higher than the estimate we obtained for Scenario 1 because Canadian producers faced a higher real wheat price over
Table 7. Scenario 2 IRR: one professional person year is added to each year throughout 1977-2005

<table>
<thead>
<tr>
<th>Based on econometric results from</th>
<th>IRR$^1$</th>
<th>IRR$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modified Almon Distributed Lag model</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Under the assumption of a perfectly elastic demand curve$^3$</td>
<td>106%</td>
<td>72%</td>
</tr>
<tr>
<td>Under the assumption that $\epsilon^C = \delta^W/\delta^S C$ :</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta = 0.2$</td>
<td>109%</td>
<td>75%</td>
</tr>
<tr>
<td>$\eta = 0.6$</td>
<td>104%</td>
<td>71%</td>
</tr>
<tr>
<td>$\eta = 1.0$</td>
<td>99%</td>
<td>67%</td>
</tr>
<tr>
<td>$\eta = 1.5$</td>
<td>95%</td>
<td>64%</td>
</tr>
<tr>
<td>$\eta = 0.2$</td>
<td>109%</td>
<td>75%</td>
</tr>
<tr>
<td>$\eta = 0.6$</td>
<td>104%</td>
<td>71%</td>
</tr>
<tr>
<td>$\eta = 1.0$</td>
<td>99%</td>
<td>67%</td>
</tr>
<tr>
<td>$\eta = 1.5$</td>
<td>95%</td>
<td>64%</td>
</tr>
<tr>
<td><strong>Geometric Combination Lag model</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Under the assumption of a perfectly elastic demand curve</td>
<td>71%</td>
<td>50%</td>
</tr>
<tr>
<td>Under the assumption that $\epsilon^C = \delta^W/\delta^S C$ :</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta = 0.2$</td>
<td>73%</td>
<td>51%</td>
</tr>
<tr>
<td>$\eta = 0.6$</td>
<td>69%</td>
<td>48%</td>
</tr>
<tr>
<td>$\eta = 1.0$</td>
<td>66%</td>
<td>46%</td>
</tr>
<tr>
<td>$\eta = 1.5$</td>
<td>63%</td>
<td>44%</td>
</tr>
<tr>
<td>$\eta = 0.2$</td>
<td>73%</td>
<td>51%</td>
</tr>
<tr>
<td>$\eta = 0.6$</td>
<td>69%</td>
<td>48%</td>
</tr>
<tr>
<td>$\eta = 1.0$</td>
<td>66%</td>
<td>46%</td>
</tr>
<tr>
<td>$\eta = 1.5$</td>
<td>63%</td>
<td>44%</td>
</tr>
</tbody>
</table>

$^1$ - when the collected data on wheat breeding are used: 1977-1991 Klein et al. (1996), 1995-2006 – based on WGRF reports
$^2$ - when we assume that the real spending per professional scientist remained constant over 1977-2006 at the level of 500 thd. 2006 dollars
$^3$ - This is equivalent to assuming that Canada is a small open economy

1977-2005 and the average real cost of a professional scientist was lower in 1977-2005 than it was in 2005.

Average annual rate of return is given in Table 8. The counterfactual in this case is ‘no wheat breeding research over 1977-2005’. As the results show without wheat breeding effort by 2006 yield index would have been about 15.6 index points lower. Over 1977-2005 wheat breeding research generated annually on average the net present value of 98 mln. 2006 dollars.

At a first glance the presented estimates of the rates of return to wheat breeding may look tremendously high and unrealistic. However, a simple calculation might persuade the reader that the rates of return cannot be low. The area weighted yield index increased from 103.88 in 1977 to 116.09 in 2006. This would not have happened had there been no breeding industry and in 2006, for example, yield index would have been 10.5% lower without research. Given
Table 8. The benefits from wheat breeding research in Western Canada

<table>
<thead>
<tr>
<th>Year</th>
<th>Change in yield, index points</th>
<th>Present value of net benefits(^1), mln. 2006 $</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MADL</td>
<td>GCL</td>
</tr>
<tr>
<td>1977</td>
<td>-4.1</td>
<td>-4.1</td>
</tr>
<tr>
<td>1978</td>
<td>-4.0</td>
<td>-4.0</td>
</tr>
<tr>
<td>1979</td>
<td>-3.7</td>
<td>-3.7</td>
</tr>
<tr>
<td>1980</td>
<td>0.20</td>
<td>11.3</td>
</tr>
<tr>
<td>1981</td>
<td>0.42</td>
<td>27.4</td>
</tr>
<tr>
<td>1982</td>
<td>0.70</td>
<td>1.17</td>
</tr>
<tr>
<td>1983</td>
<td>1.05</td>
<td>0.32</td>
</tr>
<tr>
<td>1984</td>
<td>1.45</td>
<td>-0.12</td>
</tr>
<tr>
<td>1985</td>
<td>1.91</td>
<td>0.14</td>
</tr>
<tr>
<td>1986</td>
<td>2.44</td>
<td>0.86</td>
</tr>
<tr>
<td>1987</td>
<td>3.02</td>
<td>1.97</td>
</tr>
<tr>
<td>1988</td>
<td>3.61</td>
<td>3.36</td>
</tr>
<tr>
<td>1989</td>
<td>4.26</td>
<td>4.63</td>
</tr>
<tr>
<td>1990</td>
<td>4.94</td>
<td>5.54</td>
</tr>
<tr>
<td>1991</td>
<td>5.65</td>
<td>6.75</td>
</tr>
<tr>
<td>1992</td>
<td>6.34</td>
<td>7.64</td>
</tr>
<tr>
<td>1993</td>
<td>7.04</td>
<td>8.39</td>
</tr>
<tr>
<td>1994</td>
<td>7.76</td>
<td>8.64</td>
</tr>
<tr>
<td>1995</td>
<td>8.48</td>
<td>9.46</td>
</tr>
<tr>
<td>1996</td>
<td>9.22</td>
<td>10.29</td>
</tr>
<tr>
<td>1997</td>
<td>9.95</td>
<td>11.03</td>
</tr>
<tr>
<td>1998</td>
<td>10.68</td>
<td>11.78</td>
</tr>
<tr>
<td>1999</td>
<td>11.37</td>
<td>12.13</td>
</tr>
<tr>
<td>2000</td>
<td>12.02</td>
<td>12.77</td>
</tr>
<tr>
<td>2001</td>
<td>12.68</td>
<td>13.13</td>
</tr>
<tr>
<td>2002</td>
<td>13.29</td>
<td>13.81</td>
</tr>
<tr>
<td>2003</td>
<td>13.94</td>
<td>14.84</td>
</tr>
<tr>
<td>2004</td>
<td>14.52</td>
<td>15.20</td>
</tr>
<tr>
<td>2005</td>
<td>15.05</td>
<td>16.05</td>
</tr>
<tr>
<td>2006</td>
<td>15.56</td>
<td>15.85</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>98.1</td>
<td>96.8</td>
</tr>
<tr>
<td><strong>IRR(^3)</strong></td>
<td>72%</td>
<td>49%</td>
</tr>
</tbody>
</table>

\(^1\) Assuming the real discount rate of 5%
\(^2\) Using the collected wheat breeding expenditures data
\(^3\) Assuming that the real cost per PPY was 500 thd. dollars over 1977-2005

the 2006 wheat revenue of $4.7 bln. a 10.5% increase in yield brought approximately $490 mln. of additional revenue in 2006 only. At the same time the cost of wheat breeding over 1977-2006 was about 180 mln. 2006 dollars. Of course, an increase in the yield index over 1977-2006 cannot be attributed solely to wheat breeding but rather to all wheat research with wheat breeding research accounting for about 15-25%. However, one should not forget about
the benefits that will be generated in the future beyond 2006 as higher yielding varieties are used as germplasm to develop new superior varieties and wheat research over 1977-2006 will yield additional $490 mln. many years into the future.

6.5. Limitations of the study. A few remarks about this study should be mentioned. First, it is evident that the data period with only 30 observations is short. This is especially true for estimating the geometric combination lag model where the estimation results seem to be dependent on the choice of \( n \). As Speaker et al. (1989) suggest for \( n = 7 \) or \( 8 \) the model gives a good approximation of the true lag structure. However, choosing \( n = 8 \), for example, requires the estimation of 16 parameters in the model, in which case having only 30 observations presents a limitation with respect to the degrees of freedom. Furthermore, increasing the number of observations when estimating the infinite lag models would reduce the importance of the “initial conditions” variables, which is desirable to obtain consistent estimates of the knowledge stock effects.

The primary limitation in this study relates to obtaining reliable data on wheat breeding expenditures in monetary terms, which limits our abilities to calculate the rates of return to wheat breeding. The inability to apportion particular projects reported in the ICAR database to separate the wheat breeding component might have also biased the estimate of the wheat breeding effort expressed in professional person years.

Another limitation of the study is pooling all wheat classes to arrive at an average yield index. Constructing yield index for each class of wheat and estimating the effect of wheat breeding expenditures in each separate case might have given a better estimate of the benefits of wheat breeding. However, the lack of information on research spending for different classes of wheat did not allow us to do this.

7. Conclusions

The goal of this study was to estimate the benefits of breeding research in Western Canada. This aspect was taken with respect to such an important commodity in Western Canada as wheat. The study period covered 1977-2006.

While most of the existing empirical studies on benefits from research impose certain restrictions on the lag length of research this study was an attempt to estimate the infinite distributed lags models, thus allowing for the fact that the benefits are generated by the existing knowledge stock rather than increments (investments over the last years) to this stock.

Computation of the rates of return to wheat breeding involved estimating the relationship between the area weighted yield index and past wheat breeding expenditures. Two models have been estimated: the modified Almon distributed lag and the geometric combination lag
models. The results reveal that the marginal contribution of a professional scientist to the yield index is 0.69 (0.61 in the case of GCL model), that is, adding one professional scientist in one year increases the yield index in the long-run by 0.69 (0.61) index points. Use of these estimates in the calculation of the rates of return produces the marginal rate of return to one professional scientist added in 2005 that lies in the 43-53% range (35-41%) depending on the cost of one PPY. Because of a higher real price of wheat the marginal rate of return to a professional scientist added in earlier years is even higher - 64-109% (44-73%). Such high rates of return indicate that investment into wheat breeding has shown to be highly beneficial and would warrant continued investment.

Even though investment into wheat breeding seems to be very profitable the wheat sector has not attracted much of private sector investment. One explanation might be a complex structure of wheat genome (compared to canola, for example) and, as a result, the inability to use genetic engineering techniques in wheat breeding. This, combined with Canada’s IPRs policy, allows the protection of new wheat varieties only in the form of Plant Breeders’ Rights\textsuperscript{4}. Plant Breeders’ Rights, in their turn, do not allow wheat breeders to capture the returns and farmers are able to retain most of the benefits with a one-time purchase and a subsequent reproduction of the seed (Gray, Malla (2000)). This leads to underinvestment into wheat breeding, which explains such high rates of return. Effective property rights can change the distribution of benefits from wheat breeding research as well as the rates of return by transferring a portion of the gains to wheat breeders, thus attracting more investment.

References


\textsuperscript{4}This is in contrast to canola, for example, where DNA modification techniques are used and patenting can be applied to within cell processes, which ensures de facto protection of the whole plant


