The Adoption of Molecular Marker Assisted Selection in Publicly Funded Western Canadian Wheat Breeding Programs

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Abstract

This thesis examines the adoption of marker assisted selection (MAS) by public wheat breeders in Western Canada. While governments, producers and the private sector are investing heavily in genomics and the development of breeding tools, improvements in breeding outcomes is dependent on the adoption of these new tools. The data set for this thesis was gathered from in-person surveys of eleven of the twelve active public wheat breeders in Western Canada. This nearly comprehensive data set allowed the construction of adoption curves for MAS, at the breeder level, and the breeder program level, and at the trait level, providing a detailed perspective of the level of adoption. Data collected from breeders on the year that breeders became aware of the markers they adopted provides an estimate of the adoption lag for each marker at all levels of aggregation.

Based upon review of relevant literature, variables that could affect adoption, including characteristics of the marker, breeding program, and the breeder were identified. Ordinary least square regression models are developed for both adoption lag and the number of markers used.

There is a high level of adoption of MAS by public wheat breeders with adoption lags decreasing over time. The number and type of employee influences the number of markers a breeder adopts. Absorptive capacity, how frequently a breeder reads academic publications, the number of years experience a breeder has, and whether a breeder is an employee of Agriculture and Agri-Food Canada (AAFC) all shorten the adoption lag of MAS.

Key Words:

Marker assisted selection (MAS), wheat breeding, adoption, awareness, absorptive capacity

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Dedication

For Garth, Vern, and Frank.

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Chapter 1: Introduction

1.1 Background and Rationale

Advances in genomics and biotechnology have led to the development of many powerful tools and technologies that can be used for the development of new wheat varieties. However, not all wheat breeding programs utilize the same set of technologies. New breeding tools will only impact wheat breeding if they are adopted by breeders. Understanding why breeders choose to adopt and utilize certain technologies will identify both drivers and inhibitors to adoption. This knowledge can, in turn, lead to policies that accelerate the adoption of new tools, thereby improving genetic gain and increase the economic efficiency of breeding efforts.

The focus of this research is to examine the breeder adoption of marker assisted selection[1] (MAS[2]) by publicly funded Western Canadian wheat breeders. Understanding what drives and inhibits the adoption of this technology is important because this technology offers the ability to increase the economic efficiency of wheat breeding programs. Working with eleven of twelve breeders in the public sector, who collectively dominate variety development in the region, provides a nearly complete picture of breeding activities. As one of the earliest molecular breeding tools, which continue to develop and expand, the experience with adoption of MAS provides data to gain insight into the adoption of modern breeding technologies. This research can inform the adoption of future technologies and the adoption of MAS in other sectors and regions of the world where it has yet to be adopted.

This research is part of the GE^{3}LS (genomics and its ethical, environmental, economic, legal, and social aspects) component of the Canadian Triticum Applied Genomics project (CTAG^2). The CTAG^2 project funded by Genome Canada, Genome Prairie, Western Grain Research Foundation, Government of Saskatchewan, Sask Wheat, Alberta Wheat, Manitoba

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[1] Marker assisted selection – Selection of specific breeding material based upon evaluation and identification of specific pieces of DNA, RNA, chromosomal banding, or chemical tags that are correlated with a desired trait a plant breeder is selecting for (Dreher et al., 2002; Tester, & Langridge, 2010; Caberera-Bosquet et al., 2012).

[2]Any abbreviation of marker assisted selection refers to the use of molecular markers utilized in a marker assisted selection breeding strategy.

Agriculture, and DuPont Pioneer seeks to map the wheat genome and use this knowledge to alter the future of wheat breeding (Pozniak & Sharpe, 2015). Activity 5.1, a GE^3LS component of $CTAG^2$, seeks to examine how genomics technologies are enabling the development and deployment of new breeding tools that are changing current economics of wheat breeding (Pozniak & Sharpe, 2015). As part of Activity 5.1 this thesis research examines how publicly funded Western Canadian wheat breeders are adopting and deploying the genomics based breeding tool of MAS.

Wheat is a staple food in Canada, and other countries around the world. Development of Canada's wheat production capability is important to meet both domestic and foreign demand. Canadian wheat production for the year 2015 is estimated to have totalled 27.6 million tonnes, while the next closest estimated production crop was canola at 17.2 million tonnes (Statistics Canada, 2015a). Canadian wheat exports averaged 17.7 million tonnes for the years 2014-2015; this accounted for almost half of all Canadian grain exports. The total area seeded to wheat in Canada in 2015 was estimated to have been 24.1 million acres, with the prairies provinces (Saskatchewan, Alberta and Manitoba) making up the vast majority of the acreage (estimated 24.07 million acres) (Statistics Canada, 2015b; Statistics Canada 2015c). With production and exports of Canadian wheat being vast, improving wheat productivity is economically important. The creation of better wheat varieties will benefit the economy while enhancing food security.

Wheat breeders manage their breeding programs using all available resources, tools, and techniques, with a goal of improving wheat varieties. In most breeding programs, the availability of human, physical and financial resources are limited. New tools and breeding technologies change what is possible, and can change the design of breeding programs. For instance, the development of molecular gene markers and higher capacity sequencing has increased the scope for MAS, which might replace later generation phenotypic selection. However, given resource constraints, the stochastic nature of breeding outcomes, and wide array of rapidly changing breeding tools, it is not always clear when new tools should be used. Identifying constraints and characteristics that impact the adoption of new breeding tools can help breeders accelerate adoption and enable plant breeding programs to become more efficient.

1.2 Objective

The goal of this thesis research is to understand the determinants of MAS adoption in publicly funded Western Canadian wheat breeding programs. The first objective is to quantify the level of adoption and awareness of MAS that exists within the industry as of 2016. The second objective is to examine how breeder and breeding program characteristics influence industry adoption of MAS. The magnitude of this influence will be estimated. The third objective is to examine how adoption lag associated with markers utilized in MAS has changed over time. After achieving these objectives, a general picture of breeding endeavours within the industry are presented.

Understanding how specific characteristics effect the intensity of the adoption of MAS, described by the number of markers a breeder or program utilizes, and the adoption lag associated with MAS by the trait a marker confers will lead to understanding the economics of adoption of breeder technologies. Increased understanding of what drives or inhibits adoption, creates knowledge that can foster additional innovation in wheat breeding.

1.3 Methodology Overview

The methodological framework used to study adoption in this thesis research is based upon economic theory related to the adoption of new technologies[3]. The topics this review covers; the adoption of innovations, adoption and human capital, absorptive capacity, learning by using, and economics of MAS in wheat breeding. Endogenous variables that measure MAS adoption, and variables that could influence MAS adoption are identified from the review of relevant literature. A survey instrument was used to collect the relevant data from publicly funded wheat breeders in Western Canada via in person interviews. A MAS industry adoption curve is constructed from the data. Awareness and adoption curves are constructed for each different trait type where MAS is adopted. Areas under awareness and adoption curves are calculated to determine the size of the adoption lag area, and compared to determine where markers are being adopted quickest and slowest. An econometric approach using ordinary least squares (OLS) regression analysis is used to examine the impact of relevant dependent and

[3] In this context innovation is viewed as a change in technologies, input, output, or institution used by a firm or individual. In its verb form, adoption is part of a process of innovation.

independent variables. Results from the regressions are interpreted to identify drivers and inhibitors the adoption of MAS, along with policies that could be implemented to improve adoption.

1.4 Thesis Organization

The remainder of this thesis in organised in five chapters. Chapter 2 contains a review of the relevant literature beginning with literature pertaining to the adoption and diffusion of new innovations. This is followed by studies examining how human capital impacts adoption. Literature relating to adoption and learning by using is next, followed by the absorptive capacity literature. A review of the literature pertaining to the benefits that MAS may deliver in wheat breeding programs concludes the review.

Chapter 3 uses the generic adoption literature and knowledge of wheat breeding to identify the dependent variables used to measure MAS adoption and the independent variables that could influence adoption of MAS in wheat breeding. These variables become the basis of the survey instrument used to collect data.

Chapter 4 contains an overview of the construction and implementation of the survey, beginning with information regarding the sample size, geographic location of the breeders, and the survey response rate. This is followed by a brief description of the survey questions with discussion of ways the data can be sorted and organized. This chapter concludes with a section that discusses the challenges that arose during the process of survey implementation, and some of the limitations of the data set.

Chapter 5 reports the survey results and the econometric analysis of the data. The chapter begins with an industry overview of the breeding programs included in the survey followed by description and presentation of MAS adoption curves at the industry and trait level. Simple correlation between key variables are then presented, followed by a description of the perceived reliability of MAS and markers at the trait conferred level. Econometric analyses of adoption at the breeder and program level and the adoption lag associated with MAS conclude Chapter 5.

Chapter 6 contains a summary of the thesis research. Conclusions are drawn and policy recommendations are presented. This is followed by a discussion of the thesis research, its limitations, and possible avenues for future research.

Chapter 2: Review of the Literature

2.1 Introduction

This chapter examines theory relating to the adoption and diffusion of innovations. Understanding the relevant literature pertaining to the adoption of new innovations is vital to understanding MAS adoption in wheat breeding programs. This review creates a foundation for the identification relevant variables presented in Chapter 3.

The remainder of this chapter is organized into six sections. Section 2.2 examines literature relating to the adoption of innovations over time. The role of human capital in the adoption process of new innovations is reviewed in Section 2.3. Section 2.4, discusses literature that examines *learning by using* and how it relates to adoption of innovations. Section 2.5 reviews absorptive capacity literature. Section 2.6, examines literature relating to MAS and wheat breeding, and focuses on the benefits that MAS can deliver in wheat breeding programs. Section 2.7 summarizes the chapter.

2.2 Adoption and Diffusion

The wheat industry is a significant part of the Canadian economy and as such, wheat breeding programs that develop improved wheat varieties are important. While, there have been many studies that have examined the adoption process of new technologies or innovations, most of these studies have been at the farm or firm level. Research regarding the adoption of new plant breeding techniques has largely focused upon innovations enabled through biotechnology. The most important of these works included Rogers' (1962) study on the *Diffusion of Innovations*, Griliches' (1957) *Hybrid Corn: An-Exploration in the Economics of Technological Change*, Mansfield's *Technical Change and the Rate of Imitation* (1961), and Marra et al. (2002) *The economics of risk, uncertainty and learning in the adoption of new agricultural technologies: where are we on the learning curve*.

Scholars such as Rogers (1962), Griliches (1957), Mansfield (1961), and McWilliams and Zilberman (1996) all identified that the adoption of new technological innovations exhibit an S-shaped or ogive curve, seen in Figure 2.1. The vertical axis of the graph represents the percentage of adoption of an innovation, which can range from 0 to 100 percent (Griliches, 1957; Rogers, 1962). The horizontal axis measures time, therefore the slope of the curve can be considered to be the rate of the adoption of the new innovation, with a flatter slope denoting slower adoption and a steeper slope denoting quicker adoption.

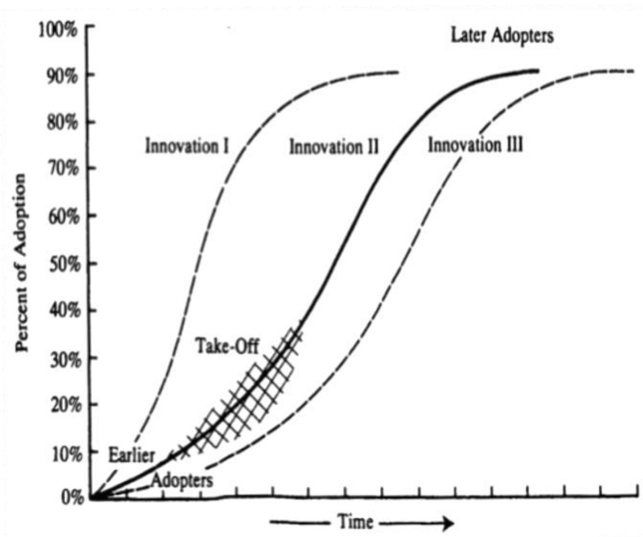


Figure 2.1 The Diffusion Process and Theoretical Adoption Curves

Source: (Rogers, 1962)

Griliches (1957) developed a model that described adoption, seen below. He noted that he tried other functional forms but the logistic functional form best fit his data to describe the S-shaped curve. Within Figure 2.2 *P* represents the percentage of planted hybrid seed, *K* represents the maximal value, *a* represents the constant of integration (places curve on time scale), *b* represents the rate of growth, and *t* represents time (Griliches, 1957).

$$P = K/1 + e^{-(a+bt)}$$

Figure. 2.2 Griliches Adoption Function

Source: (Griliches, 1957)

Rogers also highlights the reason why the S-shaped curve is shaped as such. It is a cumulative curve of industry adoption encompassing the five different classes of adopters seen in Figure 2.3.; Innovators, Early Adopters, Early Majority, Late Majority and Laggards (Rogers, 1962). Rogers asserts that once enough information about a new innovation is known, mass adoption begins to take place, described as a “take off” phase (Rogers, 1962).

In the epidemic model of adoption, the diffusion of information propels the adoption of the innovation (Geroski, 2000). In this model, there are few sources of information and adoption is relatively slow during early stages, and at later stages the diffusion process rate slows as adoption approaches a maximum level (Geroski, 2000).

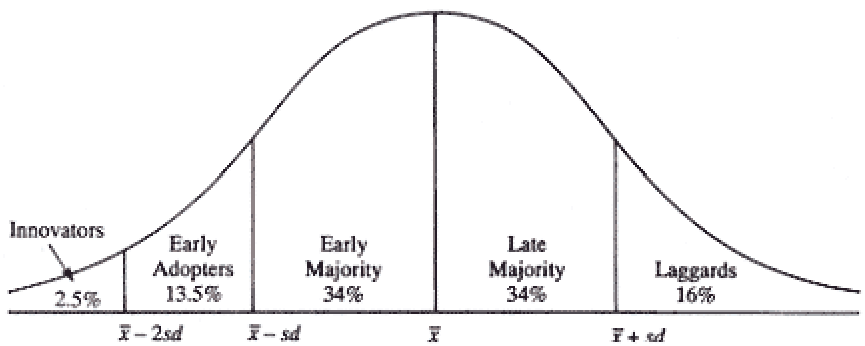


Figure 2.3 Theoretical Adoption Distribution

Source: (Rogers, 1962)

The heterogeneity model of adoption will also produce S-shaped adoption curves (Hall & Kahn, 2003). With the heterogeneity model, the value that each individual places upon the innovation differs (Hall & Kahn, 2003). The following set of assumptions are crucial to the heterogeneity model; the cost of the new innovation is constant or declines over time, individuals choose to adopt the new innovation when the value they associate with it is greater than its cost, and the distribution of values which proposed adopters have for the innovation is approximately normal (Hall & Kahn, 2003). These models that were briefly touched upon re-enforce that the diffusion of innovations over time will be S-shaped, therefore when examining the adoption of MAS in wheat breeding, one would expect the industry adoption curve to be S-shaped.

Two aspects critical to the adoption of new innovations are hardware and software (Rogers, 1962). Hardware can be thought of as the aspect that is the tangible tool that enables the innovation, while the software can be thought of as the knowledge or information base that enables the hardware aspect to be utilized (Rogers, 1962). There must exist both sufficient supporting hardware and software of an innovation for adoption to take place. These two aspects represent areas in which possible bottlenecks or inhibitors to adoption can exist (Rogers, 1962). When conceptualizing hardware and software in terms of MAS, the hardware can be thought of as the physical equipment that is needed to undertake MAS while the software is the body of genomic knowledge that exists documenting correlations between plant genetic data and trait expression.

The decision to adopt a new technology is based on a five-step process (Rogers, 1962). First, knowledge and information is gathered about the new innovation. In the second step, an opinion is constructed based upon the knowledge gathered. In the third, a decision is made whether or not to adopt the new innovation. The fourth step is the new innovation implemented into action. Lastly an evaluation is made to assess whether or not the adoption decision was appropriate (Rogers, 1962). However, Marra et al. (2002) asserts that the decision process to adopt a new innovation may include experimentation on a trial basis. Experimentation forgoes the last step of Rogers' (1962) five-step process of adoption leading to a quicker adoption process (Marra et al., 2002).

2.3 Adoption and Human Capital

The amount of human capital possessed by an individual, firm, or country is of importance in the adoption of an innovation (Nelson & Phelps, 1966; Rosenberg, 1972; Hall & Khan 2003; Wozniak, 1987; Cosar, 2011). Nelson and Phelps suggested that the level of human capital, measured in education affects the adoption of new innovations, with greater levels of human capital leading to quicker adoption (Nelson & Phelps, 1966). Rosenberg's 1972 journal article, *Factors Affecting the Diffusion of Technology,* argued that the level of skill a worker possesses is critical to a firm's successful exploitation of a new technology and therefore influences the diffusion and adoption of innovations. It is also suggested that the rate in which adoption occurs is affected by the complexity of the innovation being adopted (Rogers, 1962.; Hall & Kahn, 2003). Therefore, more complex innovations will have a slower rate of adoption and require larger amounts of human capital if they are to be successfully adopted.

Research conducted by Wozniak (1987) on Iowa Cattle firms revealed that the decision to adopt an innovation is a human capital intensive decision. Additionally, the study revealed that firms of differing size have differing rates of adoption and economies of scale exist between production and adoption (Wozniak, 1987). Research examining automation in manufacturing concluded firms are more likely to adopt new innovations if they possess a labour force that is highly skilled (Doms et al., 1997). Therefore, breeding programs that possess a larger amount of human capital reflected in the amount of skilled labour, experience, or education could affect the likelihood of MAS adoption. Breeding programs could also exhibit some forms of economies of scale that impact adoption.

2.4 Adoption and Learning by Using

Gathering new knowledge and information is vital in evaluating whether to adopt an innovation or new technology. The act of acquiring new knowledge through the utilization of a new technology or innovation is called *learning by using* (Rosenberg, 1982). Learning by using is associated with technologies or innovations exhibiting a high degree of complexity, high development and capital costs, as well as uncertainty of performance which is understood through experience and use of the technology (Rosenberg, 1982; Foster and Rosenzweig, 2010). Learning by using is also seen as context specific because of the heterogeneity of the adopters that can influence adoption either positively or negatively (Foster and Rosenzweig, 2010). In Rosenberg's 1982 book, *Inside the black box technology and economics*, he argues better understanding about the strengths and limitations of an innovation can lead to new practices that better exploit the innovation, leading to increases in efficiency and productivity. This was a factor thought to be occurring with farmers and high yielding seed varieties in developing countries (Feder et al. 1985). In their examination of high yielding seed varieties, Foster and Rosenzweig (1995) identified experience with an innovation impacting the efficiency of operation of that innovation and the rate at which it is adopted. Rosenberg (1982) identified that learning by using was occurring within the airline industry. The learning by using activity was revealed through the changes in maintenance schedules of differing aircraft engines over time (Rosenberg, 1982).

In the journal article, *Time Of Technology Adoption And Learning By Using,* McWilliams and Zilberman (1996) examine how firm size and education affect computer application usage and argue that learning by using leads to increased intensity of use of an innovation. Larger firms experience greater returns to scale in learning by using than smaller firms, due to increased operations that enable them to learn at a quicker rate (McWilliams & Zilberman, 1996). They also found that firms that possess greater amounts of education are better at learning by using as they have the ability to understand the intricacies of the knowledge and information gained from using the innovation (McWilliams & Zilberman, 1996). Thus, firm size and education influence the intensity in which an innovation is used and the rate at which the innovation is adopted; greater intensity of use leads to an increased rate of adoption (McWilliams & Zilberman, 1996). However, the greater the skill at utilizing a current technology the larger the opportunity cost of changing and moving away from that technology (Karp & Lee, 2001). Therefore, increased efficiency with a technology enabled from learning by using may impede the adoption of newer better innovations and technologies. Due to the complexities of MAS and the heterogeneity that exists within breeding programs, learning by using could affect the adoption rate within the industry as well as the intensity of utilization within those breeding programs, seen in the number of markers they use.

2.5 Absorptive Capacity

Absorptive capacity is the ability to recognize the value of new information and exploit this information for economic gain (Cohen & Levinthal, 1990). The existing stock of knowledge within the firm is of great importance in the ability to accumulate new knowledge from internal and external sources (Cohen and Levinthal, 1990; Tepic et al. 2012). Prior knowledge helps a firm identify potentially valuable information and quickly understand how this new information can complement the knowledge base of the firm (Cohen & Levinthal, 1990). Cohen and Levinthal also argue that R & D activities can contribute to a firms' absorptive capacity by increasing the ability to recognize related information that can be commercially exploited. Applying this concept, wheat breeders who possess knowledge related to genomics are more apt to utilize MAS. As well, wheat breeders using processes similar to MAS are more likely to adopt those technologies.

Cohen and Leventhal (1990) also argue that absorptive capacity requires a base level of relevant related knowledge by individuals within the firm, especially in an environment that exhibits high levels of technological change and uneven or lumpy flows of information. Applying this argument to wheat breeding, both the head breeders and workers within the breeding program must possess a base level of knowledge relating to genomics and MAS processes for adoption of MAS to occur.

For maximum performance, a firm's strategies and goals must align with their absorptive capacity and knowledge acquisition (Lichtenthaler, 2016). Therefore, knowledge developed and acquired within a breeding program that effectively increases the absorptive capacity within should be related to MAS if it is to influence MAS adoption.

In the journal article, *Absorptive Capacity: A review, Reconceptualization, and Extension*, Zahra and George (2002) examine the many different definitions of what scholars define as absorptive capacity. Zahra and George (2002) define absorptive capacity as a dynamic capability that enables a firm to capture and perpetuate a competitive advantage, through the development and use of new knowledge. This definition of absorptive capacity is similar to the definition that Cohen and Levinthal (1990) developed, but Zahra and George (2002) differ from Cohen and Levinthal (1990) in that they argue absorptive capacity can be broken into two aspects; potential absorptive capacity and realized absorptive capacity. They assert that four dimensions comprise the aspects of absorptive capacity; acquisition, assimilation, transformation, and exploitation (Zahra and George, 2002).

Micheels and Nolan (2016) argue the subjective perceptions of the ability to absorb or exploit new information can a hinder firm's adoption. If the managers' subjective perception of a firm's absorptive capacity is lower than actual capacity, the perceived capacity will limit the firms' absorptive capacity. The implication is that subjective perceptions of a wheat breeder and their views of the absorptive capacity capabilities of both the breeding program, and individuals working within, could hinder the adoption of MAS. This lower perception of absorptive capacity could retard the adoption of MAS or other related genomics technologies when in fact, the necessary absorptive capacity is present to exploit them.

2.6 MAS and Wheat Breeding

Some marker assisted selection (MAS) has been utilized by wheat breeders for the last two decades. The literature suggests MAS is used in a breeding program when usage lowers costs as compared to conventional phenotypic selection (PS) (Dreher et al., 2002; Hock et al., 2003; Dubcovsky, 2004; Tester & Langridge, 2010; Heffner et al., 2011). However, as noted by Brennan et al. (2005), the costs and values associated with the markers utilized in wheat or any breeding program vary widely. This is due to the heterogeneous nature of each individual breeding program and the estimated cost savings from utilizing MAS and specific markers that will be unique to each breeding program (Brennan et al., 2005). It is worth noting costs that are associated with the development and utilization of MAS and these aforementioned markers should decrease over time as technology related to them improves. What was once expensive and cost prohibitive years ago may not be so now.

Additionally, research has shown the use of MAS in wheat breeding programs increases genetic gain while decreasing costs up to 40 percent (Kuchel et al., 2005). However, the large cost savings and genetic gain seen by Kuchel et al. (2005) when examining a wheat breeding strategy that utilized MAS also utilized double haploid (DH) technology. Kuchel et al. (2005) note that this combination of MAS coupled with DH technology would lead to time savings when compared to a conventional breeding strategy (Kuchel et al., 2005). Furthermore, the gains that are made from a strategy that employs multiple technologies that work together to create both time and cost savings is preferable. However, due to the heterogeneous nature of breeding programs, the amount of time savings a breeder or program can capture will be different on a case by case basis, and the largest of time savings would come at initial implantation of the innovation. This leads to the conclusion that wheat breeders must select and utilize technologies that complement each other as well as their breeding strategy to optimally maximize the resources at their disposal.

There also exists an upper limit of the number of markers a breeder can reliably use in a MAS strategy each generation. The breeder therefore must weigh reducing his breeding population each time they utilize MAS for selection purposes while maintaining the desired population of plants for the next generation. Therefore, MAS is not used solely for selection of material to keep or cull but also to develop parental lines, and backcross desired traits into high performance varieties or breeding material.

2.7 Chapter Summary

This chapter reviewed the academic literature relating to the adoption of new technologies. Following the seminal work by Rogers (1962) adoption is understood as outcome of a process involving awareness, evaluation, decision making, implementation, verification. The binary decision of heterogeneous individuals, with normally distributed characteristics results in a S-shaped aggregate adoption curve. The potential benefit embodied in the innovation is a key driver for adoption. Knowledge, human capital and physical capital plays a role in the absorptive capacity of an individual or firm. Learning by using, economies of size, and institutional factors can also play a role in the adoption.

MAS is a relatively new tool for wheat breeders. The discovery of each new marker, is potentially a new tool that breeder can incorporate into their breeding program. The literature suggests this adoption decision and the timing of this decision will be influenced by many of the factors identified above.

Chapter 3: Variables of Interest in MAS Adoption

3.1 Introduction

The purpose of this chapter is to build upon generic adoption literature and knowledge of wheat breeding to identify the dependent variables used to measure MAS adoption, and to identify independent variables that could influence the adoption of MAS in wheat breeding. These variables become the basis of the survey instrument, which is described in chapter 4.

The remainder of this chapter is organized into four sections followed by a chapter summary. Section 3.2 describes a generic adoption function for MAS within publicly funded Western Canadian wheat breeding. Section 3.3 describes measures of MAS adoption, and the speed of adoption that will be used as the dependent variables in the econometric model. Section 3.4 describes the independent variables that are likely to influence MAS adoption. Section 3.5, contains information about figures that will be constructed and examined. Section 3.5 provides a summary.

3.2 The Adoption Function

As outlined in Chapter 2, a breeder's decision to use MAS for any particular trait within a breeding program is a complex process that will be influenced by many factors. In collecting primary data, it becomes vital to have a framework to systematically identify dependent variables that can be used to measure the extent and speed of adoption as well as the independent variables that can be used to measure the exogenous variables that are driving the adoption process. Fortunately, the extensive adoption literature including those studies reviewed in Chapter 2, provide considerable insight in these variables of interest.

The foundation of economic adoption theory is that agents are rational and self interested and will adopt an innovation only when they expect a benefit from doing so. However, agents differ in the benefit that they can realize from the innovation and importantly they can differ considerably in absorptive capacity and their perception of expected benefits. The expected benefits from adoption of MAS for any particular marker will be a function of the marker characteristics, the program characteristics, and the breeder characteristics. Using the literature to delve deeper into important marker characteristics, program characteristics and breeder characteristics, a comprehensive framework to examine MAS adoption is developed.

Marker characteristics are obviously important as markers can vary in the phenotypic trait they are associated with and in their reliability. A marker will be of most value when it is associated with an economically important trait and is perceived to be a 100% reliable indicator of that trait. In the adoption process outlined by Rogers (1962), individuals gather knowledge and form an opinion about the innovation, which is used in adoption decision (Rogers, 1962, Marra et al. 2002). Asking breeders to identify their perceived reliability for the different markers that they are using in MAS, can measure some of the risk aspect associated with a marker.

There are many characteristics of a breeding program that can influence the expected benefit of MAS. Breeding programs vary by wheat class, which can directly impact the value of a marker. Breeding programs vary in size, which can influence the benefits and per unit costs of using MAS. They also can vary considerably in labour and specialized technical expertise needed to use MAS. Breeding programs are also heavily influenced by facilities and equipment that can influence the absorptive capacity and the unit costs of MAS. Finally, the institutional setting for a breeding program can have large impact on the cost of shared resources, and common operational norms can spread across breeders and programs.

The characteristics of the breeder themselves can also play a large role in the expected benefits from the use of any particular marker. The literature on *learning by using* suggests that breeder experience can increase absorptive capacity and adoption. Similarly, the propensity to read scientific literature or engage in genomics research might assist evaluation of novel markers. Finally, the breeder's age could influence the planning horizon for the breeders.

This straightforward adoption model can summarize mathematically in two equations:

Adoption = *f [Expected Benefit]* (3.1)

Expected Benefit = *g [marker characteristics (expected benefit, reliability), program characteristics (size, labour, technical expertise, fixed capital, wheat class, institution), breeder characteristics (experience, education, personal interests)]* (3.2)

These two equations imply that in a reduced form, adoption will be a function of the same characteristics of the markers, breeding programs and breeders that impact the expected benefits of the innovation.

3.3 Variables to Measure MAS Adoption

Understanding the adoption of MAS is important for wheat breeding and wheat genomics. The discovery of new a molecular marker will have value, when adopted by breeders. As such, understanding when a marker is discovered, when breeders become aware of the marker, and when a breeder adopts the marker is important for innovation.

As described in chapter 2, the standard logistical S-shaped adoption curves rely very heavily on a normal distribution of potential adopters. With a small sample size of adoption, the binary decision of adopt or not adopt will not approximate a normal distribution, or fit a typical logistical curve. For example, looking at whether breeders have adopted MAS in any of their breeding programs, can yield 11 data points at most, and is unlikely to produce an smooth S-shaped adoption curve. It is also difficult to draw inferences if the adoption of markers are viewed as isolated independent events. For these reasons, more aggregate measures of MAS adoption are also used as variables to explore adoption.

Adoption of MAS can be examined as an *intensity of usage* in a number of ways. The first and most obvious is a simple count of the number markers employed over time in a program, by a breeder or by the public sector over time. A second measure of *intensity of usage* could be the number of trait categories where MAS used, at both the program and breeder level. This form of aggregation recognizes there can be several markers available for the same trait and the use of more than one would often be redundant.

Adoption lag, defined as the amount of time between a breeder's awareness of a marker and the breeder's adoption of the marker, can also be important for innovation. In the context of the adoption process defined by Rogers (1962) awareness of an innovation happens during the first step and adoption happens in the fourth step. Adoption lag length will be different for each breeder depending on the absorptive capacity and value to the breeding program. The variables that influence adoption will affect adoption lag because adoption lag is inherently within the adoption process.

3.4 Description of Independent Variables

This section describes different independent variables that can reasonably be foreseen to affect adoption of MAS.   The breeder data can be collected at their breeding program level where breeding for each class of wheat is viewed as a separate program. Once the data is collected for each breeder in each of their breeding programs, they can be aggreagated in a number of ways to compare outcomes.

The variable "Y*ear of Adoption*" is a marker trait category variable, that indicates the year of adoption for each marker. If there is *learning by using* taking place, adoption should be increasing over time and the adoption lag should decrease by year of adoption.

The variable "*Reliability*", is the perceived reliability a breeder associates with each trait category in which they have adopted the use of MAS to confer that trait. Reliability is measured as the perceived percentage probability that the presence of the marker is associated with the desired trait.

The variable "A*bsorptive Capacity Score*", is measured at the breeder level. It is measured by responses to statements from surveyed breeders. The responses to each statement are equally weighted within the final score.

The variable "B*reeder Experience*", is the number of years that a breeder has been in their current position. The variable "*Breeder Experience Squared*" is the product of the squared value of "B*reeder Experience*". Both variables relating to experience are measured at the breeder level.

The variable "*Number of Publications Read*" is measured at the breeder level. It is the number of different academic journals and publications that each surveyed breeder reported to be reading. Breeders were asked to only include academic journals and publications that they read which relates to their breeding activities.

The variable "*Frequency of Publications Read*", is the number of times within a year that a breeder reported to be reading academic journals and publications that relate to their breeding activities. This variable is measured at the breeder level.

The variable “*Number of Technical Employees*”, is measured at the breeding program level. It is defined as the number of full time equivalent technical employees a breeder oversees that are working on a specific market class of wheat. Using a full-time equivalent was done to accurately gauge the number who are working within each program, as some breeders oversee more than one program and have the same technical employee working within both programs. Measuring a variable like this eliminates double counting any technical employee. Other reasons for measuring employee variables like this are discussed in chapter 4.

The variable “*Number of Seasonal Employees*”, is measured at the breeding program level. It is the number of full time equivalent seasonal employees a breeder oversees that are working on a specific market class of wheat. It is for the same reasons as the variable “*Number of Technical Employees*”, this variable is measured in a full-time equivalent.

“*Insect Resistance*” and “*Agronomics*” are variables that are measured at the marker trait category level. Of traits that breeders have adopted markers for use in a MAS, three broad categories of markers can be identified; disease resistance markers, insect resistance markers, and improved agronomics markers. These are categorical variables and for analysis one category is omitted. The category of disease resistance is omitted, and has become the reference category.

The variable “*AAFC Dummy*” is a dummy variable. It is used to sort the breeders into two categories, breeders who are working within the AAFC and breeders who are not. When the value is equal to one it denotes a breeder works within the AAFC and when the value is zero the opposite is true. This variable is measured at the breeder level.

Table 3.1 contains the hypothesized signs of the coefficients for each of the above variables from the regressions where adoption lag is the dependent variable.

Table 3.1 Adoption Lag Regression: Independent Variables Expected Signs and Reasoning

Independent Variable	Expected Sign	Reasoning
Year of Adoption	Negative	Over time adoption of new markers within various trait categories should quicken as breeder *learn by using* MAS.
Reliability	Negative	The greater the reliability score associated with the marker the quicker adoption should take place.
Absorptive Capacity	Negative	The greater absorptive capacity of the breeder, the better and quicker they should be at exploiting new innovations
Breeder Experience	Negative	Breeders with larger amounts of experience should better understand the benefits that MAS can achieve
Breeder Experience Squared	Positive	Breeders close to retirement have larger amounts of experience and are more unlikely to invest in adopting new breeding tools. It may not make sense to invest time into a new strategy when the one they are using is sufficient
Number of Publications Read	Negative	The more publications a breeder reads the more aware they should be of innovations that can be exploited.
Frequency of Publications Read	Negative	The more frequently a breeder reads relevant publications the more aware they should be of innovations that can be exploited.
Number of Technical Employees	Negative	Technical employees are vital in certain steps that enable MAS to be undertaken.
Number of Seasonal Employees	Positive	Seasonal employees are not needed in exploitation of MAS. If a breeder is investing in larger amounts of seasonal employees, they are likely not investing in Technical employee's due to budgetary constraints.
Insect Resistance	Unknown	N/A
Agronomics	Unknown	N/A
AAFC Dummy	Positive	Institutional bureaucracy may slow down rate of adoption.

Source: (Author)

In Table 3.1, variables that are hypothesized to have the sign of their coefficients be negative are years of adoption, reliability, absorptive capacity, breeder experience, number of publications read, frequency of publications read, and number of technical employees. All else being held equal, the hypothesized negative sign means that these variables contribute to reducing adoption lag of MAS. The two variables that are hypothesized to have the sign of their coefficients be positive are number of seasonal employees, and AAFC dummy. All else being held equal, the hypothesized positive sign means that these variables contribute to increasing the adoption lag of MAS. There are also two variables where the sign of the coefficient is not hypothesized and is unknown; insect resistance, and agronomics.

3.5 Chapter Summary

This chapter was used identify the dependent variables used to measure MAS adoption, and to identify independent variables that could influence the adoption of MAS in wheat breeding. These variables become the basis of the survey instrument, which is described in chapter 4.

Chapter 4: Survey and Data

4.1 Introduction

This chapter contains four sections. These sections examine the survey that was conducted and the data that was gathered. Section 4.2 contains the response rate of the survey. It also contains the locations of the respondent breeders, and shows the areas of Western Canada in which they can be found. Section 4.3 contains an overview of the construction of the survey and the implementation of it. Section 4.4 contains a brief description of the collected survey data and the ways in which the data can be organized. Section 4.5 discusses the issues and challenges that arose during the implementation of the survey, and from the data itself. Section 4.6 provides a summary of this chapter.

4.2 Response Rate and Survey Area

This section contains an overview of the construction and implementation of the survey used in this thesis research. The survey itself can been viewed in its entirety in Appendix A. There are 12 active publicly funded wheat breeders in Western Canada, and these 12 breeders were identified as candidates to be surveyed. All 12 breeders were contacted and asked to take part in this research, 11 chose to participate. The locations of the breeders who participated can be seen in Figure 4.1. Of the 11 breeders who participated four are located in Alberta; three in Lethbridge, and one in Lacombe. Four breeders are located in Saskatchewan; two in Swift Current, and two in Saskatoon. Three breeders are located in Manitoba; two in Brandon, and one in Winnipeg. The sample size of this data is 11 and this represents an industry response rate of about 92 percent (active publicly funded Western Canadian wheat breeders). Of the 11 breeders surveyed, seven are employed by Agriculture and Agri-Food Canada (AAFC). The other four are employed at either a Canadian university or within a provincial breeding program.

Figure 4.1 Location Map of Publicly Funded Wheat Breeders Surveyed

Source:(Scribble Maps, 2017)

4.3 Construction and Implementation

The survey contains 42 questions, split into four sections. The first section contains ten fill-in-the-blank questions that seek to assess the make-up of the participants breeding program(s). The first section asks the breeder to identify the different market classes of wheat that they are engaged in breeding activities for. Also, this section asks the breeder to identify and rank the goals they wish to realize when developing a new variety. Section one also asks the breeder to state the number of years of experience they have in their current role, their highest level of educational attainment, and in what year they completed their formal education. Additional questions within this section ask the breeder to identify whether they have undertaken MAS, and whether they have been involved with the development of any markers. The final questions in this section asks the breeder to identify whether the breeding program(s) they oversee have the equipment on site to undertake MAS, whether they share equipment with another breeder and if so in what amount, and if they share employees with another breeder and if so how many.

The second section of the survey contains sixteen fill-in-the-blank style questions. These questions are designed to be filled out for each of the different market classes of wheat a breeder is developing a new variety for. Additional copies of this section were provided to the breeders when necessary. Section two asks the breeder to identify the amount of technical staff, seasonal workers, and graduate students that work within the breeding program(s) they oversee. The amounts of employees are measured in a full-time equivalency, where a unit value represents an employee who works a standard 40 hour work week. This second section asks the breeder to identify the average level of educational attainment of the technical staff they oversee, and if any of the technical staff possess the knowledge to independently undertake MAS. This section also asks the breeder to identify the number of parental lines their breeding program(s) utilize in a typical year, how many of those lines exhibit markers for desired traits, and typically how many crosses do they make when they start to develop a new variety. An additional question that asks the breeder to identify how many offspring from initial crosses made are brought forward in each generation for continued variety development within the breeding program. The final questions ask the breeder to disclose the total budget of the breeding program(s) they oversee, the percentage of that budget allocated to MAS, the percentage of that budget allocated to PS, what the dollar per line amount to undertake MAS within the breeding program(s) is, and what the dollar per line amount to under take PS within that same program(s) is.

The third section of the survey contains eleven questions. Ten of the 11 questions in this section are designed to measure the level of absorptive capacity of a breeder. The breeder is asked to read and respond to ten statements by marking on a line segment where they fell. This line segment is a continuous scale from one to ten, where one represents strongly disagree and ten represents strongly agree. Measuring the length of line segments and where a breeders' response falls, provides a continuous numerical value for all of the questions. The final question of this section asks the breeder to identify which academic journals and publications they read, and how frequently they read them. The breeders were also asked to rank the publications that identified to consume in order of their importance from one to ten; the rank of one being the most important and ten least important.

The fourth and final section of the survey contains five short answer questions, and a table. The table contains a list of known traits exhibited in wheat that have markers associated with them, this list was developed from a public online database of wheat markers (MASWheat, 2016). This table asks the breeder to identify for all the traits that they use a marker to confer that trait for, which market class of wheat are they using that marker for, what year did they first use a marker to confer that trait, what year did they become aware of a marker that could be used to confer that trait, whether the marker that they use is reliable, and to score (by percentage) the reliability. Additional blank spaces in the table were provided for the breeder to identify any category of traits that may have been over looked. The first of the five short answer questions ask the breeder to identify whether they have changed technologies or breeding practices within their career and to elaborate. Additional questions ask the breeder to identify why or why not do they utilize MAS in the wheat breeding program(s) they oversee, and in their opinion what are the most important factors limiting their use of MAS. The second last question asks the breeder to identify what they think is the most important limiting factor in MAS use in Canadian wheat breeding. The final question of the survey asks the breeder if they think genomic selection will ever become the primary tool used for breeding wheat.

Due to the nature of the small size of the publicly funded Western Canadian wheat breeding industry, care was taken to have no contact with any of the target population before implementing the survey. This was done to ensure that the sample would be unbiased from any prior contact. When constructing and refining the survey, input was sought from two retired plant breeders and one active plant breeder in a similar species. During the surveys development, the number of questions within the third section was reduced from twenty-five to ten as to mitigate against possible survey fatigue. The statements within section three were developed out of review of literature[4] relating to absorptive capacity, and adoption of innovations. The choice was made by the author to focus on an absorptive capacity score that contained both potential and realized aspects as to create one easily interpretable score.

This thesis research project met the criteria for an ethics waiver exemption and was issued one on October 24th, 2016. All breeders who chose to participate were asked to sign a consent form and retained the right to withdraw from participating in the survey at anytime. All information that was collected will be presented in a way that protects confidentiality and preserves every participating breeders' anonymity. The surveys were recorded to ensure accuracy of reported results and all data gathered from this research will be stored following the guidelines that were set forth in the consent form signed by the participants. The breeders were

[4] These statements were developed out of reviewing literature from Cohen and Levinthal (1990), Zahra and George (2002), Tepic et al. (2012), Gellynuck et al. (2014), and Micheels and Nolan (2016).

surveyed in person at the place of their employ. The surveys were conducted over the month December 2016 and the first week of January 2017.

4.4 Description of the Data

The data that was gathered is primary data and can be sorted and organized in different ways. There is breeder level data, program level data organized by market class, and marker trait category level data. When sorting and organizing the data at the breeder level, the sample size contains 11 observations. When sorting the data at the breeding program level and organizing it by market class, the sample increases in size to 23 observations. When sorting and organizing the sample data by marker trait category the number of observations increases in size to 158. At the breeder level, and the program level organized by market class, the number of observations within the sample is small.

4.5 Challenges and Issues

The overall level of participation and enthusiasm of the breeders surveyed in this thesis research was outstanding. The co-operation of almost the entire industry to allow for the requisite time necessary to complete the survey and gather the data was greatly appreciated.

However, there were challenges and issues associated with the data. The number of observations within the sample data is small when sorted by breeder or by breeding program organized by market class. When comparing differences between AAFC wheat breeders and non AAFC wheat breeders it must be noted that these groups are very small; there are seven AAFC breeders and four non AAFC breeders. Also, not all breeders completed every question of the survey. Most breeders found the second section to be long in completion, and in some case they provided a total amount of a certain figure as a question response and then provided percentages associated with the differing programs that they oversee to provide a more specific answer to the question. For example, breeder "X" oversees two breeding programs, a CWAD program and a CPS program. They have a total mixed budget of 1 million dollars and 75 percent of the budget is spent on the CWAD program and 25 percent is spent on the CPS program. Therefore, the total budget associated with breeder "X's" CWAD program is 750,000 dollars, and the total budget associated with their CPS program is 250,000 dollars. Written responses superseded any verbal responses that were given, except in the circumstance where no written answer was provided.

There were a few instances where breeders omitted responses in section four of the survey, as to the year of awareness for certain marker trait categories, however those breeders did provide information of the year of adoption for that marker trait category. Therefore, it can be inferred that at minimum the year of awareness could be the year of adoption, as adoption cannot occur without awareness.

4.6 Chapter Summary

This chapter contained information relating to the construction and implementation of the survey used in this thesis research. It shows the location of all the surveyed breeders. This chapter had a section highlighting the differing ways in which the survey data can be sorted and organized. This chapter also contains an overview of the questions within each section of the survey. Additionally, there is a section in this chapter that discussed the issues and challenges that arose from the implementation of the survey and the gathered data. The next chapter presents the results of this thesis research.

Chapter 5: Results

5.1 Introduction

This chapter decribes the data and results from the survey of wheat breeders. Section 5.2 contains an overview of the current publicly funded wheat breeding industry in Western Canada. Section 5.3 describes MAS adoption and awareness. Section 5.4 presents a series of figures depicting correlations between variables of interest at the breeder level. Section 5.5 reports the perceived reliability of markers and Section 5.6 reports regression results for breeder adoption, breeding program adoption, and adoption lag. Section 5.7 provides a summary of this chapter.

5.2 Industry Overview

An overview of the breeding activity, organised by wheat classification, is presented in Figure 5.1. The eleven wheat breeders surveyed each typically bred for more than one market classification of wheat. These are considered as distinct wheat breeding programs in our analysis.

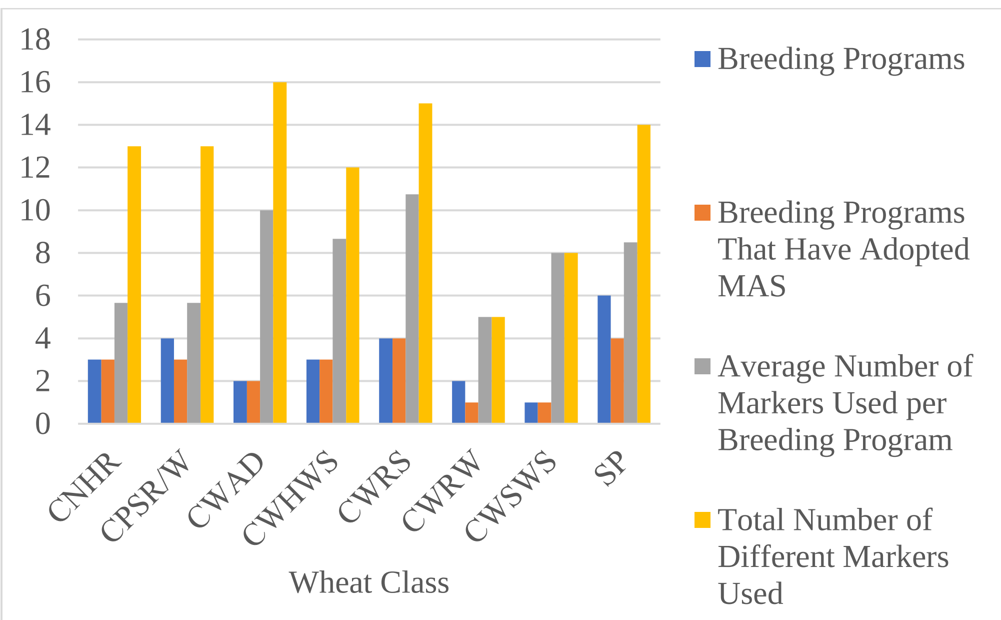


Figure 5.1 Western Canadian Wheat Breeding Overview

Source: (Breeder Survey, Authors Calculations)

As of 2016 the surveyed breeders operated a total of 25 breeding programs producing varieties for nine different Canadian Grain Commission (CGC) defined wheat market classifications, representing 90 percent of the total possible wheat market classifications. None of the public breeders surveyed identified breeding Canadian Western Extra Strong (CWES) wheat. Because some breeders did not indicate whether they were breeding Canadian Prairie Spring Red (CPSR) or Canadian Prairie Spring White (CPSW) these two categories are combined as single category for analysis.

5.3 Adoption and Awareness

5.3.1 Adoption Rate of MAS by Active Wheat Breeders within the Industry

Figure 5.2 illustrates the breeder adoption of MAS between 2002 and 2016. The curve is close to linear with a slope of .56 breeders per year, which approximitely translates to a new breeder adopting MAS every two years (1.86 to be exact). This pattern of industry adoption of MAS by active breeders is not consistent with Griliches (1957) and Rogers' (1962) findings that adoption of innovations resembles an "S" shape curve. Using the five categories of adopters as defined by Rogers (1962), and given that breeder adoption of MAS has reached 82 percent, MAS is in the late stage of adoption and only the "laggards" are left to adopt MAS.

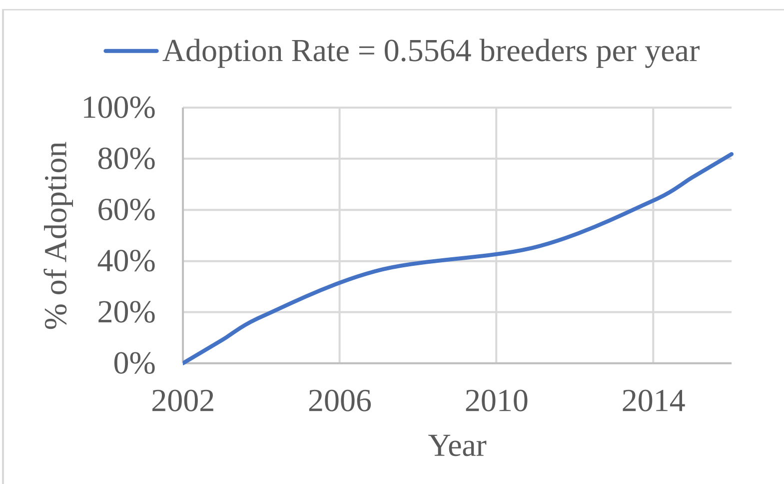


Figure 5.2 MAS Adoption by Active Breeders in Publicly Funded Western Canadian Wheat Breeding

Source: (Breeder Survey, Authors Calculation)

In the sample, MAS has been used for 21 different trait categories listed in Table 5.1. On average, wheat breeders have adopted MAS for nine trait categories with the range varying from 1 to 15 categories. Nine breeders have adopted MAS for traits conferring improved disease resistance, eight breeders have used MAS for improved insect resistance, and seven breeders used MAS for improved agronomics. Delving into the adoption data at a finer level; nine breeders adopted the use of at least one fungi resistance marker, eight breeders adopted at least one quality and yield marker, five adopted at least one abiotic stress resistance marker, and no breeder has adopted the use of viral resistance markers.

5.3.2 Adoption Rate and Awareness Rate of MAS by Active Breeders - Organized by Trait

The use of MAS differs by the market class of wheat. Figure 5.1 reports the total and average number of different traits where markers are being used for each different market class of wheat as of 2016. Four wheat breeding programs do not utilize MAS. The programs that utilize the least number of markers on average are CWRW, CWSWS, and CWHWS. The programs that utilizes the highest number of markers on average are the CWRS programs, which is the dominant class of wheat grown in Western Canada. The CWAD programs utilize the largest number of different markers and they also utilize a reduced cadmium concentration marker that is only applicable to the CWAD market classification of wheat.

The awareness of markers and adoption of MAS for 21 trait categories, is reported in Table 5.1. The trait categories are sorted in ascending order of the 2016 adoption rate. The most extensive adoption has been for rust markers and protein content with over 70% adoption across all breeders. The lowest rates of adoption have occurred in economically unimportant or market class specific traits. For instance, powdery mildew resistance is viewed as generally unimportant to most breeding programs. The breeder who had adopted MAS to confer this trait identified this desired trait as a goal specific to the market class he was breeding for. As mentioned previously, reduced cadmium concentration is only relevant for the two CWAD breeding programs, where both breeders had adopted MAS. Vernalization is only important to winter wheat breeders. Market class specific traits, and traits that are less important to the goals of breeding programs, may be why many of the trait categories still have low marker and MAS adoption rates.

The earliest MAS adoption occurred 13 years ago in 2003. This first adoption of MAS was for a marker associated with improved rust resistance (Stem, Leaf, and Combined). As reported in Table 5.1 the bulk of the trait categories within the table have had markers available for about 10 years.

Table 5.1 shows that awareness of prospective markers generally happens two to four years before the adoption of MAS. In other words, it takes two to four years for early adopters to implement the use of a marker into their breeding program(s). There are many exceptions to the 2 to 4 year adoption lag; Thousand Grain Weight -- Grain Size Gene (nine years), ESTBT Resistance (eight years), Powdery Mildew Resistance (seven years), Strip Rust Resistance (five years), Stem Rust Resistance (less than a year), Seed Coat Colour (less than a year), Wheat Stem Sawfly Resistance (less than a year). When considering lag between awareness and adoption it is important to note that breeders were only asked to report the year of awareness of a marker if they had adopted it. Also, two adopters did not report the awareness year, in those instances, the year of adoption was also used as the year of awareness.

When examining and comparing Figure 5.2, Table 5.1, and Appendix B, the industry level adoption rate of MAS differs from that of trait level adoption rates as can be seen in the shapes of the curves they exhibit. Table 5.1 shows which category of adopter the last current breeder to adopt can be labeled as. These different categories, defined by Rogers (1962) are; Innovator, Early Adopter, Early Majority, Late Majority, and Laggards. These categories are used to define what stage of adoption each marker trait category is exhibiting. There are six marker trait categories where Innovators are the current category of adopters, five where Early Adopters are the current category of adopters, four where Early Majority are the current category of adopters, and six where Late Adopters are the current category of adopters.

The difference in what category of adopter each marker trait category exhibits may be caused by the heterogeneous nature of the breeders themselves and their goals related to the market class of wheat they are breeding. Anecdotal evidence from breeder comments suggest that available resources that have been inherited from a previous regime will affect this as well.

Table 5.1 Adoption and Awareness Rates by Trait Conferred

Marker Trait	First Year of Breeder Awareness	First Year of Breeder Adoption	Latest Year of Breeder Adoption	2016 Industry Adoption	Current Category of Adopter(s)
Tan Spot Resistance	2003	2006	2006	9.09%	Innovator
Lipoxygenase	2004	2006	2006	9.09%	Innovator
Thousand Grain Weight -- Grain Size Gene	2005	2016	2016	9.09%	Innovator
Eyespot, Septoria Tritici Blotch, Toxin (ESTBT) Tolerance Resistance	2006	2014	2014	9.09%	Innovator
Powdery Mildew Resistance	2007	2014	2014	9.09%	Innovator
Seed Coat Color	2015	2015	2015	9.09%	Innovator
Reduced Grain Cadmium Concentration	2001	2003	2014	18.20%	Early Adopters
Starchy Proteins: Waxy Mutants	2008	2010	2015	18.20%	Early Adopters
Vernalization	2002	2006	2015	27.30%	Early Adopters
Grain Texture	2004	2006	2015	27.30%	Early Adopters
Midge Resistance	2008	2010	2014	27.30%	Early Adopters
Dwarfing Genes	2002	2006	2015	36.40%	Early Majority
Gluten Strength	2002	2006	2015	45.50%	Early Majority
Pre Harvest Sprouting Tolerance	2004	2006	2015	45.50%	Early Majority
Wheat Stem Sawfly Resistance	2004	2004	2015	45.50%	Early Majority
Stem Rust Resistance	2003	2003	2015	54.60%	Late Majority
Leaf Rust Resistance	2001	2003	2015	63.60%	Late Majority
Combined Rust Resistance	2001	2003	2015	63.60%	Late Majority
Fusarium Head Blight (FHB) Resistance	2002	2004	2015	63.60%	Late Majority
Stripe Rust Resistance	2001	2006	2016	72.70%	Late Majority
High Grain Protein Content	2003	2006	2015	72.70%	Late Majority

Source: (Breeder Survey, Authors Calculations)

Table 5.2 reports the areas underneath all adoption and awareness curves calculated in Appendix B. Adoption lag area is the difference between the area under the awareness curve and

Table 5.2 Areas Under Adoption and Awareness Curves, Adoption Lag Area and Lag Area Over Time

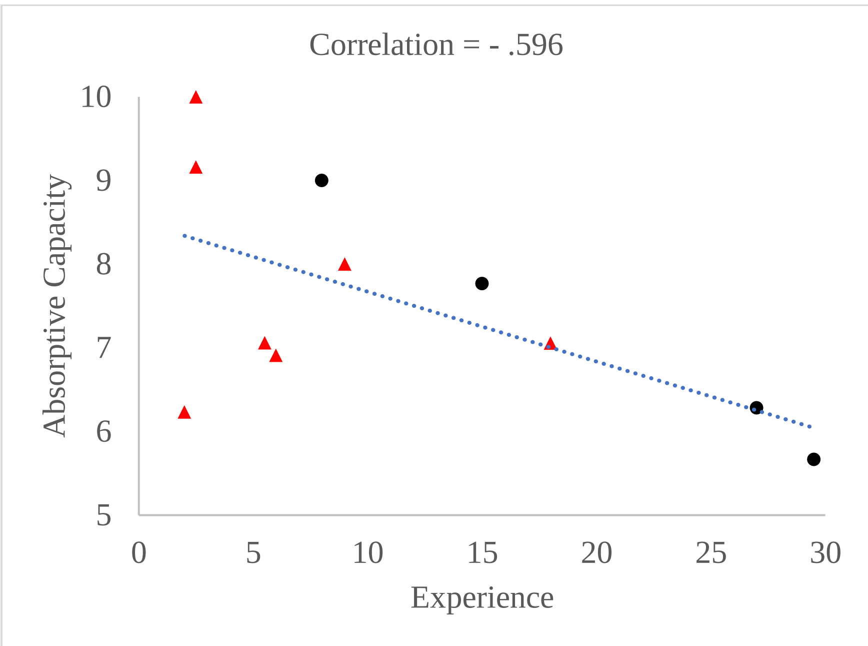
Marker Trait	Awareness Area	Adoption Area	Adoption Lag Area	Adoption Lag Area Over Time	Current Category of Adopter(s)
Tan Spot Res.	1.23	.955	.273	.019	Innovator
Lipoxygenase	1.14	.955	.182	.014	Innovator
Thousand Grain Weight -- Grain Size Gene	1.09	.045	1.05	.087	Innovator
ESTBT Tolerance	1.55	.227	1.32	.12	Innovator
Powdery Mildew Res.	1.68	.227	1.46	.146	Innovator
Seed Coat Color	.046	.046	0	0	Innovator
Reduced Grain Cadmium Concentration	2.36	1.46	.909	.061	Early Adopters
Vernalization	3.36	1.68	1.68	.112	Early Adopters
Grain Texture	2.36	1.23	1.14	.087	Early Adopters
Starchy Proteins: Waxy Mutants	1.77	.727	1.05	.116	Early Adopters
Midge Res.	1.68	1.32	.364	.04	Early Adopters
Dwarfing Genes	2.96	1.46	1.5	0.1	Early Majority
Gluten Strength	3.46	2.32	1.14	.081	Early Majority
Pre Harvest Sprouting Tolerance	3.32	2.23	1.09	.084	Early Majority
Wheat Stem Sawfly Resistance	2.5	2.14	.364	.028	Early Majority
Leaf Rust Resistance	6.23	4.5	1.73	.108	Late Majority
Stripe Rust Resistance	5.91	4.55	1.36	.085	Late Majority
Combined Rust Resistance	6.05	3.18	2.86	.179	Late Majority
FHB Resistance	5.59	3.68	1.91	.127	Late Majority
Stem Rust Resistance	3.91	2.82	1.09	.078	Late Majority
High Grain Protein Content Gene	4.91	3.82	1.09	.078	Late Majority

Source: (Breeder Survey, Authors Calculation)

the adoption curve. Since awareness and adoption do not happen at the same rate each curve will have a different slope and in turn all adoption lag areas exhibit a different shape. For an accurate comparison of the differing marker trait categories and their associated adoption lag areas they must be compared over time. The span of time that is used is the time of first awareness by any breeder within the industry to the latest adoption of a breeder within the industry. The trait that has the largest adoption lag area is combined rust resistance, and with the smallest area is seed coat colour.

5.4 Correlations

The following correlations in section 5.4 have been constructed using Microsoft Excel 16 and the correlations between two variables of interest calculated in STATA 14.



Red triangles — AAFC wheat breeders Black circles — Other wheat breeders

Figure 5.3 Experience vs. Absorptive Capacity

Source: (Breeder Survey, Authors Calculation)

Figure 5.3 shows a negative correlation of -.596 exists between absorptive capacity score of a breeder and the number of years of experience they possess. When the two variables are plotted against each other, the data appears to be heteroskedastic. There is a larger variance in a breeders' absorptive capacity score who possess less experience than breeders who possess greater experience. The reason heteroskedasticity exists between these variables may be because less experienced breeders do not fully know the bounds of their abilities and their programs capabilities. This could lead to less experienced breeders exhibiting absorptive capacity scores that are artificially raised or lowered. Less experienced breeders could also have less opportunity to exercise their absorptive capacity with less chance to develop it. The negative correlation observed between these variables could be explained by more experienced breeders spending less effort to develop their absorptive capacity and using technologies or practices they have become accustomed to (Cohen and Levinthal, 1990). This path dependence could lead to the locking out of the ability to exploit new ideas over time; if this “lock-out” persisted it would materialize in breeders who had a larger number of years of experience having a lowered absorptive capacity score (Cohen and Levinthal, 1990., Lichtenthaler, 2016). More experienced breeders exhibiting lower absorptive capacity scores near the end of their career as it becomes futile to seek out and evaluate new innovations that cannot be implemented prior to retirement.

In Figure 5.3 there exists a difference in shape between the data points of non AAFC breeders and AAFC breeders. There appears to be a greater variance in the AAFC breeder’s relationship of their absorptive capacity score to that of non AAFC breeders. It must again be noted that this shape may only exist due to the small sample size of each group within the data.

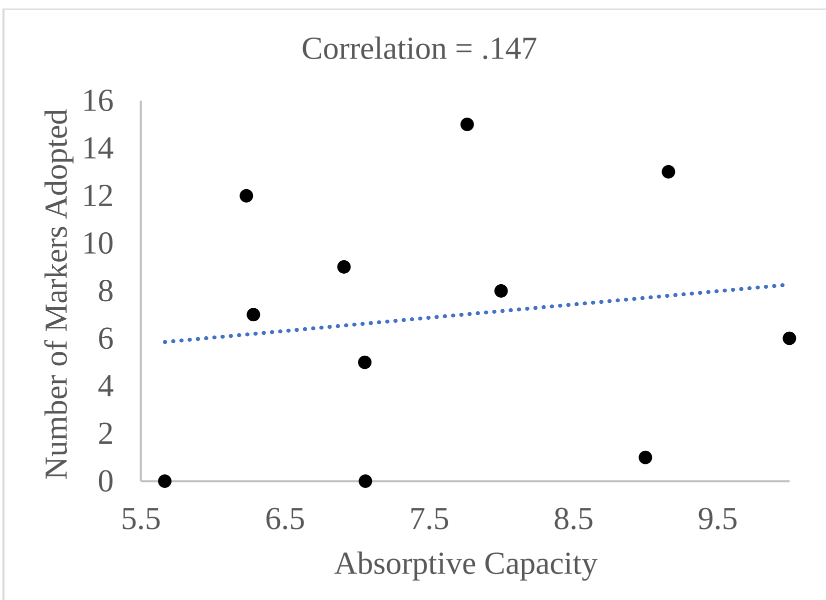


Figure 5.4 Absorptive Capacity vs. Number of Markers Adopted

Source: (Breeder Survey, Authors Calculation)

Figure 5.4 shows an extremely low correlation of .147 exists between the number of markers adopted by a breeder and their absorptive capacity scores. *A priori*, it was expected that a strong correlation between absorptive capacity and the number of markers adopted would exist. The lack of correlation is not consistent with results from Micheels and Nolan (2016), which suggest absorptive capacity is strongly correlated with the adoption of new technologies. Greater absorptive capacity allows a potential adopter to more accurately assess the benefits of adopting. The above graph illustrates that this is not the case. Due to the small sample size other factors that may influence the significance of this relationship could not be controlled for. These other factors could be related to specific goals within the breeding program, path dependence, lock out, other technologies that are available, breeder's management of best efficiency mix, belief in certain markers ability to imbue the desired trait, lack of genomic data to support desired and predicted outcome, or lack of desired markers that are perfect or near enough perfect for the breeders wished endeavours.

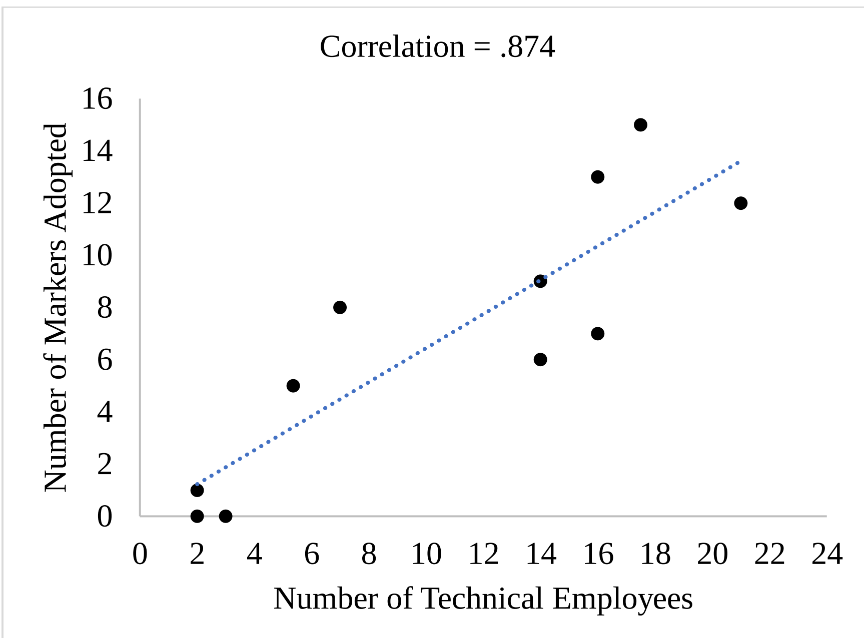


Figure 5.5 Number of Full Time Equivalent Technical Employees vs. Number of Markers Adopted

Source: (Breeder Survey, Authors Calculation)

Figure 5.5 shows a positive correlation of .874 between the number of technical employees a breeder oversees and the number of markers a breeder has adopted. This correlation is likely positive due to the technical aspects involved with carrying out MAS, such as DNA extraction. DNA extraction is a crucial and important part of utilizing MAS. Having many technical employees within a breeding program able to independently handle all aspects related to DNA extraction be quite valuable to the breeder and program. It would seem that the larger number of technically skilled employees that exist within a breeding program, the larger number of markers a breeder can utilize. This leads to the thought that economies of size exist within breeding programs. A reason for this is because a breeder can delegate tasks and utilize their technical employees efficiently. This would enable time-savings allowing the breeder to utilize their expertise at more critical stages, such as evaluation of material to either keep or cull. The causation could also run in the opposite direction, those programs using MAS must hire technical employees to operate the breeding program.

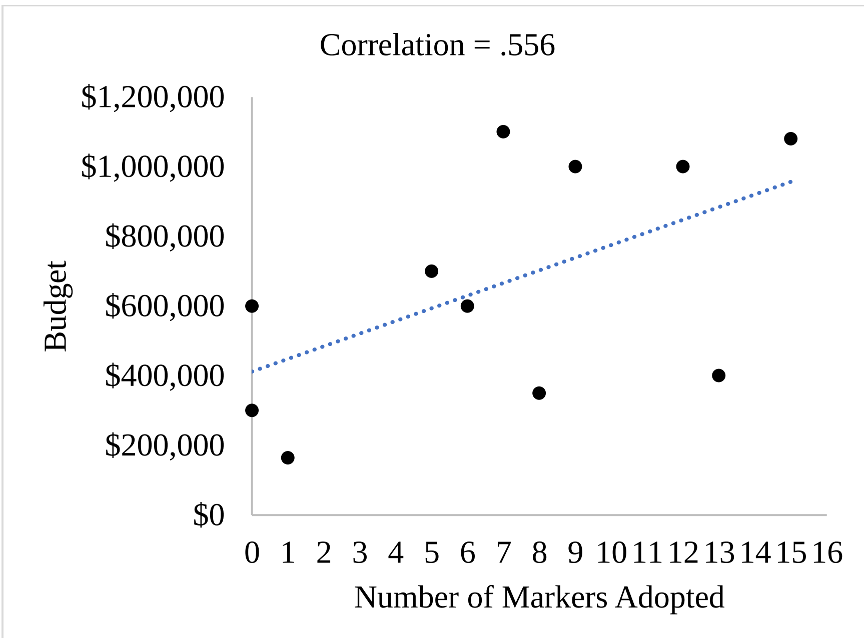


Figure 5.6 Budget vs. Number of Markers Adopted

Source: (Breeder Survey, Authors Calculation)

Figure 5.6 illustrates the relationship that exists between the budget a breeder has available and the number of markers they have adopted. The correlation between these two variables is positive and has a value of .556. A hypothesis that may explain this positive relationship is that larger budgets are needed to confirm the presence of desired traits that have low heritability. Utilizing a new marker may require a larger budget to confirm both reliability and validity of the marker for future use. It is worth noting not all markers are perfect markers that confer the desired trait 100 percent of the time, therefore during the development of a new variety, certain traits may need to be confirmed phenotypically as well. A larger budget would allow a breeder to structure their breeding program(s) in such a way that they are able to create gains in efficiency by hiring of specialized labour to help with less breeder intensive parts of MAS, leading to the idea that breeding programs exhibit economies of size. Most breeders have reported low costs to carry out MAS and there are steps of MAS where automation of the process is replacing employees. One such place is the vital step of DNA extraction, however even though the process is automated, it still must be monitored by technically skilled workers to ensure accuracy. Some of the surveyed breeders indicated that a large portion of costs associated with MAS is related to the employment of technically skilled employees who oversee this process. Therefore a larger budget would be correlated with an increased number of markers adopted.

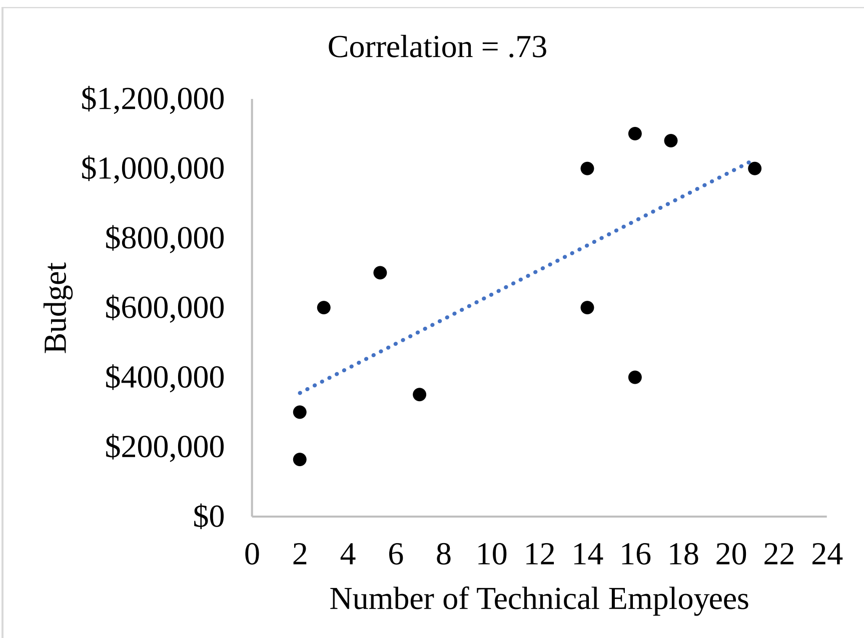
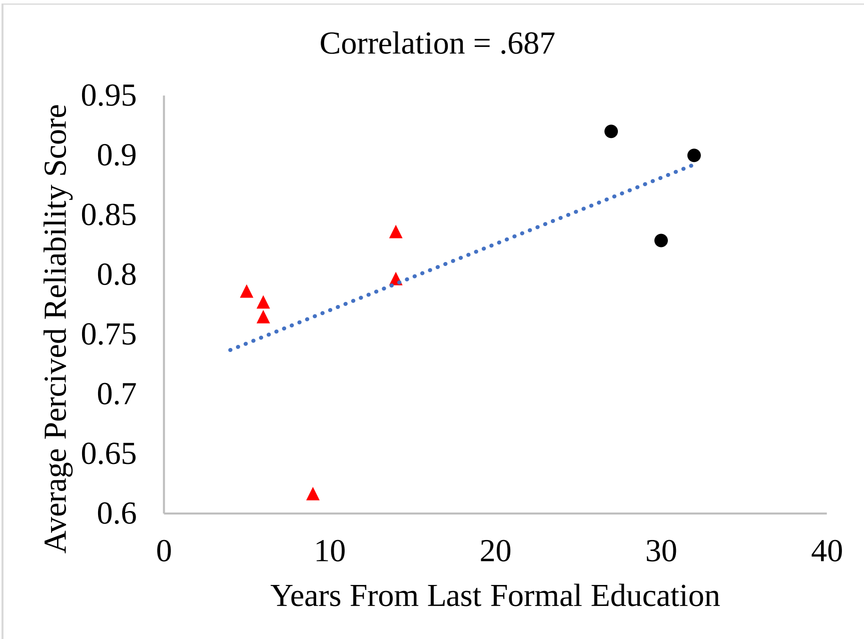


Figure 5.7 Budget vs. Number of Full Time Equivalent Technical Employees

Source: (Breeder Survey, Authors Calculation)

There is a strong positive correlation of .73 between the number of full time equivalent technical employees a breeder oversees and the budget for their breeding programs. The dollars that fund these programs are public funds which carry with them the implied assumption they are to be allocated in an efficient manner, otherwise those funds may not be accessible in the future.

Figure 5.7 shows that the larger the budget, the more technical staff that is employed by the breeder. These employees help the breeder accomplish the goals and objectives of the breeding program(s) they oversee. These employees also oversee vital steps in the MAS process. The larger number of technically skilled employees, the larger the budget needed. A larger budget also enables the hiring of more technically skilled employees. These hiring's help to achieve the goals and objectives within a breeding program. Thus, a breeder strives to use the public monies in the most efficient way to accomplish a program(s) desired outcomes and goals.



Red triangles – AAFC wheat breeders Black circles – Other wheat breeders

Figure 5.8 Average Perceived Reliability of Markers vs. Years from Last Formal Education

Source: (Breeder Survey, Authors Calculation)

Figure 5.8 shows a positive correlation of .687 exists between the average perceived reliability score a breeder associates with markers they have adopted and the number of years since a breeder finished their formal education. All breeders who participated in the survey identified the completion of a Ph.D. as their highest educational attainment. Breeders who adopted MAS into their respective program(s) are the only breeders represented in Figure 5.8. The correlation that exists in Figure 5.8 is of interest because it appears that more recent graduates are more pessimistic about the reliability of markers they have adopted into use. However, it may be that recent graduates who oversee breeding programs are using newer markers which are inherently less reliable at conferring the desired traits. Sorting the data into two groups, AAFC wheat breeders, and Non-AAFC wheat breeders, the AAFC breeder group contains more newer graduates than the Non-AAFC breeder group. The Non-AAFC group contains breeders primarily located at universities. The difference in the average perceived reliability of markers may be driven by a positive institutional bias of those breeders located at universities.

5.5 Perceived Reliability of MAS by Wheat Breeders

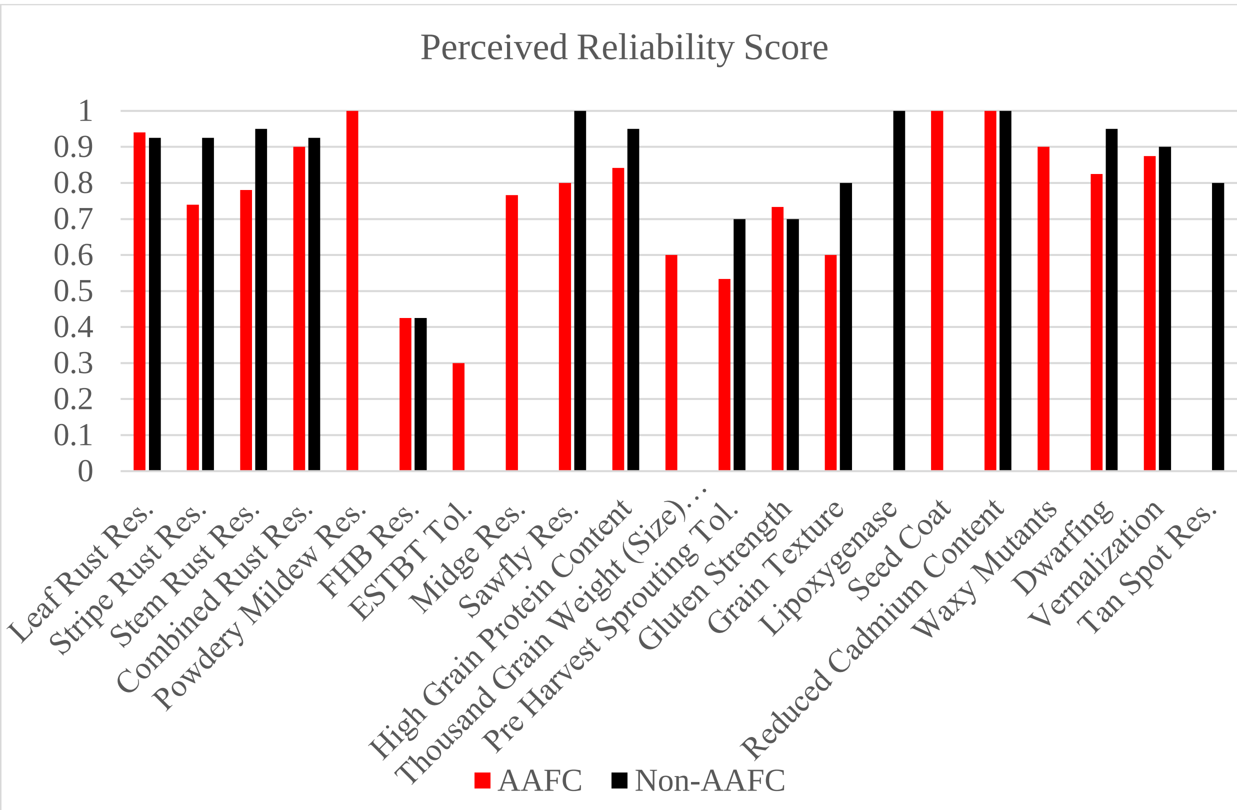


Figure 5.9 Perceived Reliability of Markers Adopted

Source: (Breeder Survey, Authors Calculation)

Section 5.5 examines the average perceived reliability of the different category of traits where breeder adoption of markers used in MAS has occurred. Figure 5.9 graphically illustrates the differences in the average levels of perceived reliability of markers to confer a desired trait between AAFC wheat breeders and Non-AAFC wheat breeders. Exact values of average perceived reliability for each trait and each group can be found in Table 5.2.

Across all traits except for gluten strength and leaf rust resistance, Non-AAFC breeders have equal to or greater average perceived reliability of markers at conferring the desired trait than AAFC breeders. Both groups of breeders have the same level of average perceived reliability of markers associated with conferring fusarium head blight resistance, and reduced grain cadmium concentration. Again, it must be noted that only the CWAD breeders utilize reduced cadmium concentration markers and these markers are only applicable to them. Supplementary graphs in Appendix C visually contrast differences between the groups of AAFC breeders and Non-AAFC breeders. Within Appendix C there are two sets of graphs. The first set of graphs highlights differences between these groups by organizing them by the number of years they are from completion of their formal education (Ph.D.). The second set presents the graphs by grouping the breeders by the amount of experience they possess. It can be seen in the graphs of Appendix C and Figure 5.8 the larger amount of years of experience a breeder posesses and the larger amount of time they are from completion of their formal education (Ph.D.), the greater average perceived reliability they reported. Non-AAFC wheat breeders have greater confidence in markers at conferring associated trait than AAFC wheat breeders. Non-AAFC breeders have on average more years' experience than AAFC wheat breeders. This could be due to recent turnover of AAFC wheat breeders.

5.5.1 Institutional Bias of Perceived Reliability of MAS by Current Adopters Organized by Trait Conferred

Table 5.3 reports the breakdown of breeders' average perceived reliability of markers at conferring the associated trait. The data set is organized into three groupings, the first group is the industry average perceived reliability as of 2016. The first column is the average of every breeder surveyed perceived reliability score of markers at conferring the associated trait. The second and third columns are the Non-AAFC, and AAFC breeders' average perceived reliability of adopted markers at conferring the associated trait. An example of this would be that breeders not within the AAFC on average utilize leaf rust markers that they believe to be 92.5% reliable.

The fourth column in Table 5.3 is the average perceived reliability scores AAFC breeders responded to have with markers they have adopted that confer the associated trait. For instance, the average reported perceived reliability by AAFC breeders of stem rust resistance markers at conferring said trait is 74%.

Table 5.3 Average Perceived Reliability of Markers

Marker Trait Category	Industry Average Perceived Reliability	Non-AAFC - Average Perceived Reliability	AAFC - Average Perceived Reliability	Difference Between AAFC and Non – AAFC
Leaf Rust Resistance	93.6%	92.5%	94%	-1.5%
Stripe Rust Resistance	79.3%	92.5%	74%	18.5%
Stem Rust Resistance	77%	95%	78%	17%
Combined Rust Resistance	90.71%	92.5%	90%	2.5%
FHB Resistance	42.5%	42.5%	42.5%	0%
Powdery Mildew Resistance	100%		100%	
ESTBT Tolerance	30%		30%	
Tan Spot Resistance	80%	80%		
Wheat Stem Sawfly Resistance	85%	100%	80%	20%
Midge Resistance	76.7%		76.7%	
High Grain Protein Content Gene	86.9%	95%	84.2%	10.8%
Pre Harvest Sprouting Tolerance	60%	70%	53.3%	16.7%
Gluten Strength	72%	70%	73.3%	-3.3%
Grain Texture	75%	80%	60%	20%
Starchy Proteins: Waxy Mutants	90%		90%	
Reduced Grain Cadmium Concentration	100%	100%	100%	0%
Thousand Grain Weight -- Grain Size Gene	60%		60%	
Lipoxygenase	100%	100%		
Seed Coat Color	100%		100%	
Dwarfing Genes	88.8%	95%	82.5%	12.5%
Vernalization	88.3%	90%	87.5%	2.5%
Total Average Perceived Reliability	79.8%	86.3%	76.6%	9.7%

Source: (Breeder Survey, Authors Calculation)

The final column in Table 5.3 is the difference between the AAFC and Non-AAFC breeders average reported perceived reliability of markers each group has adopted at conferring the associate trait. The final row in Table 5.3 is the difference between the two groups. There are differences between the groups' perceived reliability scores across the 13 different marker trait categories that are shared. The largest difference between the two groups' is for markers that confer stripe rust resistance and grain texture.   The final row in Table 5.3 is the average across all marker categories for each grouping.

The difference between AAFC and Non-AAFC wheat breeders total average perceived reliability of markers at conferring traits is 9.7%. The difference is lower at 8.9% across the marker trait categories where they both have adopted markers within those trait categories. This suggests an institutional bias may exist in the perceived efficacy of markers used in MAS.

5.6 Ordinary Least Squares Regression Results

The following regressions presented in this section are linear OLS regressions. Organizing the data in different ways allowed for multiple avenues of analysis. In the first set of regressions, the dependent variable is the number of markers adopted. Two regressions were identified as containing statistically significant results. In the first of these regressions, the data set is organized at the breeder level. In the second regression it is organized at the breeding program level (defined by market class). In the second set of regressions the dependent variable is adoption lag of the differing markers at the trait level where MAS adoption has occurred. Three different regressions are presented. All regressions were computed in STATA 14 with the use of robust standard errors to correct for heteroskedasticity that was present.

When organizing the data set by breeder the number of observations is 11. When organizing the data set by breeding program the number of observations is 23. At both the breeder and program level the number of observations is small. This small sample size limits the ability to control for all variables and characteristics that may influence the number of markers adopted (intensity of MAS use). Organizing the data set by the adoption lag associated with the trait categories where MAS adoption has taken place the number of observations is 158.

5.6.1 Regression Results – Number of Markers Adopted by Breeder

There are limitations using regression analysis when the data set is organized at the breeder level. The sample size at this level is very small. This presents a degrees of freedom issue associated with carrying out regression analysis. As the number of independent variables increases the degrees of freedom decreases quickly. Omitting variables to preserve degrees of freedom is not an avenue to pursue, as bias may be created within the regression (omitted variable bias) and it may lead to misspecification of the model. However, this analysis was undertaken to identify candidate variables to use in the OLS regressions when the data is sorted at the breeding program level and when the sample size is larger.

A very basic OLS regression was undertaken which regressed the numbers of markers a breeder adopted against the number of full time equivalent technical employees the breeder oversees working within the programs(s) they manage. The results are statistically significant at the .05 level and the regression has an adjusted R^2 value of .737. The number of markers a breeder has adopted into use is predicted to change by .652 for every additional full-time equivalent technical employee they manage. Only one right hand side variable was used to predict the number of markers adopted. Other variables from the data captured were expected to possess explanatory power at this level, however this was not the case.

5.6.2 Regression Results – Number of Markers Adopted by Program

It was identified that technical employees have a statistically significant impact upon the number of markers adopted when the data is organized at the breeder level. Therefore another regression was undertaken to examine the influence employees have on the number of markers adopted at the breeding program level. Organizing the data by breeding program increases the sample size to 23. Table 5.4 shows that the number of both fulltime equivalent seasonal employees, and technical employees have a statistically significant effect on the number of markers adopted by a breeding program. These employee level variables are significant at the .01 level. When organizing the data at the program level, variables such as absorptive capacity score and years of experience were omitted. This again is due to the small sample size of 23 and if they were to be controlled for, they would again decrease the degrees of freedom. It must be stated again that the possibility of omitted variable bias may exist, as some variables cannot be controlled for.

Holding all else constant, the number of markers adopted into use within a breeding program is predicted to increase by 0.661 for every additional fulltime equivalent technical employee who works within that program. Holding all else constant, the number of markers adopted into use within a breeding program is predicted to change by -1.32 for every additional fulltime equivalent seasonal employee working within that program.

Table 5.4 Regression Results Number of Markers Adopted by Program

Variable	Coefficient (Standard Error)	t-Statistic
Constant	5.61^{+} (1.11)	5.06
Number of Technical Employees	.661*** (.179)	3.68
Number of Seasonal Employees	-1.32*** (.447)	-2.95
R2 (Adjusted R2)	.434 (.377)	
** Significance at the .05 level		
***Significance at the .01 level		
$^{+}$Significance at the .001 level		
Number of Obs. = 23		
Model Adjusted for Heteroskedasticity (Utilized Robust Errors)		

Source: (Breeder Survey, Authors Calculations)

5.6.3 Regression Results – Adoption Lag by Marker Trait Category

Examining the data at the marker trait category level, there are 158 observations of adoption across the nine breeders using MAS within their breeding programs. The amount of adoption lag observations at this level is 127. The reason there are not 158 observations is because both an adoption and awareness date are needed to compute adoption lag. Some breeders surveyed failed to provide an awareness date, and for that reason the sample for the regressions found in Table 5.5. is 127. For all regressions in Table 5.5 the dependent variable is adoption lag, which is measured in years.

The regression model number one (base model) contains three right independent variables; year of adoption, reliability, and absorptive capacity score. All three variables are statistically significant at the .01 level and the adjusted R^2 of the model is .086. The sign of the coefficient for the variable year of adoption is negative, the sign of the coefficient for the variable reliability is positive, and the sign of the coefficient for the variable absorptive capacity score is negative. Holding all else constant, an increase to the absorptive capacity score of a breeder will decrease adoption lag. The same negative effect can be seen on the coefficient of the variable year of adoption, indicating that (holding all else constant) adoption lags have decreased over time. Holding all else constant, greater reliability scores of markers used in MAS are associated with increased adoption lag lengths. While this result is the opposite of expectation, it should be noted that the reliability of marker tends to increase over time, which could lead to positive correlation between adoption lag and reliability.

In model 2, variables are added to the model 1 to control for the following; the number of technical employees, the number of seasonal employees, if a breeder is an AAFC breeder or not, and the broad category of trait type of marker used. The two employee variables are added because they have been shown to be statistically significant in the previous subsections regressions, and may influence adoption lag length. The reference group for this regression is the adoption lag associated with Non-AAFC breeders (AAFC dummy = 0) whom have adopted a marker that confers the trait of disease resistance.

In this model the year of adoption is not statistically significant at the .05 level. The following variables are statistically significant at the .01 level; absorptive capacity score, number of technical employees, number of seasonal employees, the AAFC dummy variable, and the agronomics trait category variable. The category variable insect resistance is significant at the .001 level.

Holding all else constant, marker reliability has a positive effect upon adoption lag length. This result is consistent with model 1. Holding all else constant, absorptive capacity and the number of technical employees, both have a negative effect upon adoption lag. Holding all else constant, an increase of one full time equivalent technical employee is predicted to decrease the associated adoption lag by .119 years. Holding all else constant, the variable number of seasonal employees has a positive effect upon adoption lag and an increase of one full time equivalent seasonal employee is predicted to increase the associated adoption lag by .46 years.

Examining the categorical and dummy variables, all three were found to be statistically significant and the signs of their coefficients negative. This means that adoption lag of AAFC breeders is shorter than Non-AAFC breeders[5]. Holding all else equal, AAFC breeders adopt markers quicker than Non-AAFC breeders; AAFC breeders have an associated adoption lag 2.72 years smaller than Non-AAFC breeders.

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[5] Tables which illustrate differences in average adoption lag lengths between AAFC breeders and Non-AAFC breeders are found in Appendix D.

Table 5.5 Adoption Lag Regression Results: Model 1, Model 2, and Model 3

Variable	Model 1		Model 2		Model 3	
	Coefficient (Standard Error)	t-Statistic	Coefficient (Standard Error)	t-Statistic	Coefficient (Standard Error)	t-Statistic
Constant	1.28 (.848)	1.51	2.84 (.111)	3.50	.236 (1.66)	0.14
Year of Adoption	-.101** (.046)	-2.22	.122 (.111)	1.10	.33*** (.123)	2.69
Reliability	2.39** (.962)	2.49	1.96** (.852)	2.30	1.57** (.727)	2.16
Absorptive Capacity Score	-.464** (.204)	-2.28	-.581*** (.178)	-3.26	-1.91** (.76)	-2.51
Breeder Experience					-1.42*** (.493)	-2.88
Breeder Experience Squared					.0419*** (.013)	3.18
Number of Publications Read					3.2*** (.935)	3.42
Frequency of Publications Read					-.061*** (0.018)	-3.40
Number of Technical Employees			-.119*** (.046)	-2.58	.001 (.04)	0.02
Number of Seasonal Employees			.46*** (.149)	3.09	-.0127 (.169)	-0.07
Insect Resistance			-1.99[+] (.504)	-3.95	-1.74[+] (.471)	-3.69
Agronomics			-1.54*** (.481)	-3.21	-1.62[+] (.403)	-4.02
AAFC Dummy			-2.73*** (.939)	-2.91	-8.09*** (2.58)	-3.14
R2 (Adjusted R2)	.107 (.086)		.408 (.368)		.543 (.495)	

**Significance at the .05 level, ***Significance at the .01 level, [+]Significance at the .001 level

Reference Group Non-AAFC Breeder (AAFC Dummy = 0), and Disease Resistance Marker Trait Type

Number of Obs. = 127, Model Adjusted for Heteroskedasticity (Utilized Robust Errors)

Source: (Breeder Survey, Authors Calculations)

Holding all else constant, the magnitude of effect associated with the categorical variable insect resistance has a magnitude of effect of -1.96. This indicates that if the marker trait type that has been adopted confers insect resistance, the associated adoption lag is predicted to be 1.96 years shorter than disease resistance. Holding all else constant, the categorical variable agronomics has a magnitude of effect of -1.54. This indicates that if the marker trait type that has been adopted confers improved agronomics the associated adoption lag is 1.54 years shorter than disease resistance.

The final regression in Table 5.5, model 3 is the complete model. It contains the same right-hand side variables in model 2 with the addition of; breeder experience, breeder experience squared, number of publications read, and frequency of publications read. The variables pertaining to experience are there to control for a breeder's experience level; a more experienced breeder should have a better understanding of how to accomplish their desired wheat breeding goals. The variable breeder experience squared is the square product of breeder experience and it is to control for the lock in and path dependence a breeder would experience the longer they are in their position and closer to retirement. The idea behind this is that more experienced breeders are less likely to switch breeding practices, and change the way they accomplish their goals. The right-hand side variables number of publications read, and frequency of publications read are included to control for how a breeder becomes informed of advancements in their field.

The independent variables contained within model 3 are all statistically significant except for the variables number of technical employees, and number of seasonal employees. Holding all else equal the variable year of adoption has a positive sign of the coefficient and a magnitude of .399. As can be seen in the reduced model (model number one) the breeders within the industry could be said to exhibit learning by using MAS because the sign of the coefficient for year of adoption is negative. This negative sign of the coefficient means that the adoption lags of markers that breeders became aware of earlier are longer than adoption lags of markers that breeders have become aware of more recently. However, in the full complete model, model 3, this is not the case. The coefficient for year of adoption is now positive, and the industry does not exhibit learning by using. Breeders within the AAFC have shorter adoption lags when compared to breeders not within the AAFC, this could be due to institutional effects at work. Model 3 enables a better understanding and picture to be developed.

The variables absorptive capacity score, reliability, insect resistance, agronomics, and AAFC dummy have the same sign of the coefficients as in model 2. The magnitudes of the predicted effect have changed. Holding all else constant, the magnitude of effect on the variables AAFC dummy (large) and agronomics (small) have increased, while the magnitude of the category trait type variable insect resistance has decreased.

Holding all else equal, the variable number of publications read has a predicted effect of increasing adoption lag by 3.2 years for each additional publication read by a breeder. Holding all else constant the variable frequency of publications read has a predicted effect of -.061 years on adoption lag for every additional instance a breeder reads an academic publication per year.

The variable breeder experience has a predicted effect of decreasing adoption lag by 1.42 years for every additional year of experience a breeder accumulates, assuming all else is held constant. Holding all else constant, the variable breeder experience squared increases adoption lag by .042 years for every additional year of experience a breeder accumulates. Summing these two experience effects[6] together shows that breeders with 18 years of experience tend to have the shortest adoption lags and are predicted to have a trait MAS adoption lag 11 years shorter than a breeder with either 1 year or 33 years of breeding experience. Hence the stage of career has a very large impact on adoption.

5.7 Chapter Summary

This chapter provided an overview of the breeding efforts within the industry as of 2016 and their usage of MAS as of 2016. An adoption curve of MAS within the industry was presented. It also contained graphs depicting correlations between variables, and reasoning why such correlations may exist. Current adoption and awareness rates of each trait category where markers and MAS have been adopted by breeders was also presented and examined. Areas underneath adoption and awareness curves, and adoption lag areas were calculated and compared. Breeders perceived reliability of markers at conferring different traits was also presented and an institutional bias was uncovered. This chapter reports the results of the OLS regressions outlined in the methodology section of this thesis. It was discovered that the type of employee affects the number of markers a breeder or breeding program have adopted differently. The level of experience a breeder possess was predicted to impact trait MAS adoption lag. Absorptive capacity, perceived reliability of markers, the institution a breeder works within, and

[6] Appendix E contains a figure depicting the predicted experience effect.

the number and frequency of academic publications a breeder reads all influence breeder trait MAS adoption lags.

In the next chapter, the results from the econometric analysis will be discussed more in depth and conclusions will be drawn. Also, policy implications and recommendations based upon the results from this chapter will be made.

Chapter 6: Conclusions

6.1 Introduction

This chapter contains a summary of the thesis research. This summary is found in section 6.2. This is followed by section 6.3 which discusses policy implications, and policy recommendations are suggested. Section 6.4 discusses the limitations of this thesis research. Section 6.5 concludes this chapter and thesis. This last section explores further avenues of study, and suggests other research that should be explored.

6.2 Thesis Results Summary

This thesis research provided an overview of both the level and rate of MAS adoption and MAS awareness in publicly funded Western Canadian wheat breeding programs. An industry snap shot of 2016 wheat breeding endeavours was presented. Adoption and awareness rates of MAS and breeders perceived reliability of markers (organized by trait) was uncovered and presented. This research identified characteristics of breeders and breeding programs that were shown to be drivers or inhibitors to MAS adoption. These characteristics were explored and the directionality of effect and magnitude of the effect were also presented.

Through econometric analysis, it was discovered that the number of full time equivalent technical employees have a positive effect upon the number of markers a breeder has adopted for MAS, both at the breeder level and program level. At the program level (defined by CGC market class) it was found that the number of full time equivalent seasonal employees has a negative effect upon the number of markers a breeder adopted for use in MAS. This was consistent with literature from Doms et al. (1997) that employees who possess greater amounts of human capital are needed to exploit an innovation.

Further, econometric analysis revealed that the number of years experience a breeder has both positively and negatively impacts the adoption lag associated with individual markers utilized in MAS. The greater the number of years experience the breeder has the smaller the adoption lag, while the squared value of the number of years experience a breeder has is shown to increase adoption lag. This leads to a conclusion that mid-career breeders are most efficient at adopting markers and as time progresses their associated adoption lag worsens. Results also indicate that absorptive capacity negatively affects adoption lag. The greater absorptive capacity a breeder possess the smaller the associated adoption lag. This is consistent with absorptive capacity literature from Cohen and Levinthal (1990), and Zahra and George (2002) related to the ability to exploit new innovations for economic gain.

Learning by using is occurring within the industry; this was identified in model 1 which is the reduced model that examines adoption lag. The institutional effect, that appears in model 2 and 3 suggests AAFC breeders adopt markers faster. This might have something to do with scale of the general availability of the technical resources required for adoption. The perceived reliability score a breeder associates with a marker negatively influences the associated adoption lag. Anecdotal evidence from select breeders suggests they only adopt markers once they are known to be reliable. This line of reasoning is consistent with the idea that markers for traits have, and will continue, to improve over time. As improvement occurs, the markers will be adopted. This leads to larger perceived reliability scores of markers having a positive effect on adoption lag. Insect resistance trait and agronomic trait markers have smaller adoption lags than disease resistance.

When examining the effect technical and seasonal employees have upon adoption lag those variables were seen to have the same directionality of effect on the number of markers adopted. However, once other variables were controlled for and the full model was analyzed technical and seasonal employees proved to be non-significant in influencing adoption lag.

The amount and frequency of academic publications a breeder reads are shown to influence adoption lag. The greater the number of different journals a breeder read, the larger the adoption lag. This could be due to increased breeder awareness associated with developments in MAS from reading a variety of publications. The more often a breeder read academic publications the smaller the adoption lag. The more often a breeder reads the greater likelihood they are going to be aware of more recent advances in marker capabilities used in MAS, thus leading to smaller adoption lags.

The current industry adoption rate of MAS by breeders is 82% percent. There are 21 different marker trait categories in which markers have been adopted for use in MAS. The industry adoption curve is not ogive or “S” shaped and is not consistent with literature from

Rogers (1962), Griliches (1957), Mansfield (1961), and McWilliams and Zilberman (1996). The adoption and awareness curves of markers organized by trait conferred seem to be instead, cubic with differing points of inflection. The results uncovered in this thesis are consistent with other adoption of agricultural innovations that do not exhibit an ogive or “S” shape, such as semi-dwarf rice, telephones, semi-dwarf wheat, and fertilizer use (Alston et al., 2005). Alston et al. (2015) presents a figure in their review of U.S. productivity growth which shows adoption curves for major agricultural innovations, where most of those innovations do not exhibit an ogive or “S” shape.

6.3 Policy Implications and Recommendation

Results from this research indicate that larger amounts of technically skilled employees lead to the increased intensity of MAS usage. If the public funds are available, increasing funding to provide public breeders with larger budgets to hire more technically skilled workers should lead to increasing the intensity of MAS usage within the industry. However, if the assumption holds that these breeders are efficiently allocating their funding, “laggard” breeders whom have not adopted MAS will continue to exist within the industry because the monies from increased funding would flow to the most efficient breeding programs and maximize social welfare in the process. The affordability utilizing MAS within a breeding program could be a constraint. Two of the surveyed breeders identified that the United States Department of Agriculture as having research laboratories which provide equal access to genomic related services to all publicly funded USDA affiliated breeders. As a result USDA affiliated breeders to not require the equipment needed to undertaken MAS within the breeding programs they oversee, and instead use these laboratories for that service. If policy was developed to enable such laboratories to exist in Western Canada it could make MAS more affordable for all publicly funded Western Canadian wheat breeders, and increase MAS adoption by reducing or eliminating the constraint of costs associated with MAS.

Both Simple Sequence Repeats (SSRs) and Single-nucleotide polymorphism (SNP) markers are being used in breeding activities. Breeders who are still utilizing systems and technology related to SSR markers have indicated they would like to transition to utilizing systems and technology that support SNP markers. Breeders have expressed that SNP markers are the superior type of marker. Shaping policy to increase funding could help transition those breeding programs that partially use SSRs markers to wholly use SNP markers.

Increased genomic information leading to improved markers is necessary for increased adoption taking place. One breeder suggested the reason they do not utilize MAS is because the genomic information is not fully uncovered for the type of material they are working with, and other technologies offer better outcomes. However, if policy is enacted to increase basic research funding, and budgetary funding it could lead to full industry adoption.

In this thesis research, the AAFC has been shown to have smaller adoption lags associated with adopting markers into use for MAS. Enacting policy to help other breeders become part of the AAFC network or developing a network modeled after the network found within the AAFC, could lead to faster adoption.

6.4 Limitations of the Thesis Research

The limitations of this thesis research relate mainly to the data. There are a very small number of publicly funded wheat breeders in Western Canada. Undertaking econometric analysis with a very small sample sizes poses a host of issues. As stated previously eleven of the twelve breeders participated in this thesis research, almost the entire population of the public wheat industry, which dominate the wheat breeding in Western Canada. When grouping breeders by AAFC breeders and Non-AAFC breeders it should be noted that each group is small; four Non-AAFC breeders and seven AAFC breeders. There are inherent limitations with using such small groupings to make comparisons, as over or under representation can result. The high response rate allowed for a nearly complete picture to be developed of the current applications of MAS in publicly funded Western Canadian wheat breeding, and the current activities of members within the industry.

An endogeneity issue of bidirectional causality potentially exists between the number of markers adopted and the number of technical employees within the regressions that examine the intensity of MAS usage at the breeder and breeding program level. This endogeneity issue may exist because the number of markers a breeder adopts may influence the number of technical employees. While not explored in this thesis, this endogeneity issue could be resolved using instrumental variable (IV) regression analysis where a suitable instrument for the number of technical employees has been identified.

Model 1 in section 5.6.3 identified learning by using to be occurring within the industry. With the addition of other variables and a variable to control for the institution a breeder works within it was then found that learning by using was not occurring. The institutional effect that was identified is that AAFC wheat breeders have much smaller adoption lags for markers than non-AAFC wheat breeders. This thesis research did not explore whether learning by using was occurring within an institution, such as the AAFC. This is an area that could be explored in future study.

The social and professional networks that a wheat breeder has developed could impact the adoption of MAS. The network diffusion of information relating to MAS could influence breeders and breeding programs by number of markers they use and the adoption lags associated with markers at conferring differing traits. The influence could be either positive or negative and was not explored or controlled for within this thesis research.

A breeder's graduate students could also impact MAS adoption. The research that graduate students carry out is a potential source of information for breeders to become aware of new advancements related to MAS and genomics. The concept of graduate students being a source of information was not examined within this thesis research.

The development of markers that can be utilized in wheat breeding occurs world-wide. The intellectual property rights (IPR) could inhibit the ability of breeder or breeding program to adopt those markers. This influence of IPR structures was not explored or controlled for within this thesis research.

The data suggests that two differing cohorts of breeders exist and can be defined by years of experience; less experienced breeders and more experienced breeders. This bimodal distribution of breeders could have influenced MAS adoption. This was not controlled for or explored within this thesis research. Follow-up research in few years when the demographics have shifted could examine this as a factor in adoption.

Increasing the amount of data by gathering from additional sources would have led to an increased sample size. However, this is not without its own issues as the underlying characteristics of the population sampled in this research may be supressed or exaggerated as new respondents would have had to be added from the private sector, another country, or breeders working with different crop types. It is assumed breeders who participated in this survey provided accurate information and the survey was completed truthfully and in good faith. However due to the nature of surveys, the responses from the respondent group must be taken at face value. Ensuring the veracity of their responses and in turn, the data, is difficult.

6.5 Suggested Future Study

An avenue of further related study could be to survey private sector wheat breeders in Western Canada, which would increase the amount of data that could be used for analysis. Securing the participation of private firms could be difficult as they might need a large incentive to expose possible sensitive information. Gathering additional data on conference attendance and networking would help to discover what influence that has on adoption lag and the intensity of usage of MAS.

Identification and data collection for a suitable instrument for the number of technical employees variable should be undertaken. This would allow for IV regression analysis to take place and resolve the endogeneity issue of bidirectional causality that could exist within the OLS models in section 5.6.1 and 5.6.2.

The addition of an interaction variable between year of adoption and AAFC dummy should be added to model 2 and model 3 within the regressions examining the adoption lags of markers used in MAS. The resulting directionality of the sign of the coefficient and whether the interaction variable is significant would identify if learning by using is occurring within the AAFC.

Identification of how the bimodal distribution of wheat breeders by years of experience influences MAS adoption should be explored. It would also be worth replicating this thesis research five or more years from now as those more experienced breeders within this industry may have exited and a more normal distribution of breeders organized by years of experience may exist.

Another avenue could be to conduct research of this type in the United States, as they have large numbers of publicly funded wheat breeders.

There exists the potential to conduct this type of research on other breeders and programs working with other cereals in Western Canada. With this data, one could either increase the sample size within this study or utilize the new sample for analysis. Pursuing this avenue of potential research allows for uncovering drivers and inhibitors of MAS adoption in other cereal crop types. Also, the possibility of carrying out this type of research with other breeders and programs outside the cereal family could lead to an interesting comparison study between all crop types. This may lead to a better understanding of how to improve implementation of new genomics based breeding tools and innovations.

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Appendix A

Breeder Survey

Survey Contact

Name:

Position:

Employer:

Section 1 – The questions in the following section are related to the make-up of your breeding program.

Defined by Canadian Wheat classifications what and how many different classifications of wheat are you currently breeding new varieties for?

____________________ ____________________ ____________________

____________________ ____________________ ____________________

____________________ ____________________ ____________________

1. How many years have you been in your current role? ____________________

2. What is your level of professional education? ____________________

3. What was the year of completion of your professional education?

   ____

4. What is the goal of your breeding activities in development of a new variety within each of the Canadian Wheat classifications you are developing new varieties for? Please numerically rank the goals from least to most important.

   ____________________ ____________________ ____________________

   ____________________ ____________________ ____________________

   ____________________ ____________________ ____________________

5. Have you ever used marker assisted selection (MAS)? __Yes __No. (Follow up ---If No please explain why not)

6. Have you been involved with the development of any markers?

   No__ or How many? __

7. Does your breeding program currently possess the equipment required to undertake MAS on site? ___________________
8. Do you share equipment with another breeder, if so how much? ___________________

9. Do you share employees with another breeder, if so how many? ___________________

Section 2 – The answers provided for this section will be related to each different classification of wheat defined by Canadian Wheat classifications that you are engaged in breeding activities for. Additional copies of this section will be provided for each different classification.

Wheat Classification: ___________________

10. How many full time equivalent technical staff does your breeding program employ? ___________________
11. How many full time equivalent seasonal workers does your breeding program employ? ___________________
12. How many full time equivalent graduate and post-graduate students does your breeding program employ? ___________________
13. What is the average education level of your permanent technical staff?

    ___high school ___diploma ___degree ___masters ___PhD

14. How many parental lines does your breeding program currently utilize in a typical year? ___________________

15. How many of the aforementioned parental lines exhibit markers for desired traits that you are engaged in breeding activities for? ___________________

16. Typically, how many initial crosses do you make when beginning to develop a new variety? ___________________

17. Typically, how many offspring from the initial crosses do you select to bring forward in each generation of your breeding program? (Example – F_2 300, F_3 200, …etc.)

___________________ ___________________ ___________________

___________________ ___________________ ___________________

18. Do your permanent technical staff within the breeding program currently possess the knowledge to independently undertake MAS? ___________________

19. Do your graduate and post-graduate students within the breeding program currently possess the knowledge to undertake MAS? ___________________

20. What is the total budget of your breeding program? ___________________

21. What is the dollar amount of your budget that is dedicated to each classification you are developing a new variety for? ___________________

22. What is the percentage of budget allocated to MAS? ___________________

23. What is the dollar per line amount to undertake MAS in your breeding program?

____

24. What is the percentage of your budget allocated to Phenotypic Selection (PS)?

____

25. What is the dollar per line amount to undertake PS in your breeding program? (Follow up – if known please indicate the dollar per line per trait amount)

___________________ ___________________ ___________________

___________________ ___________________ ___________________

Section 3 – Absorptive Capacity – This section is meant to help identify the level of absorptive capacity within your breeding program. Absorptive capacity is the ability to recognize the value of new information and exploit this information for gain, which is vital to the creation and exploitation of innovations. In this framework, this refers to any economic or genetics gain related to your breeding activities.

***When answering mark with a line where you fall on the scale eg.**

______________________________/_____________

27. I am constantly looking at ways to increase the efficiency of the breeding program.

1 ____ 10

Strongly Disagree Strongly Agree

28. I as well as the employees within the breeding program interact with professionals within my industry to obtain new knowledge.

1 ____ 10

Strongly Disagree Strongly Agree

29. I am able to quickly recognize new innovations and opportunities that can be exploited within plant breeding.

1 ____ 10

Strongly Disagree Strongly Agree

30. I am able to collect and catalogue new knowledge so that it may be utilized in the future.

1 ____ 10

Strongly Disagree Strongly Agree

31. I am able to understand and react to changes in the plant breeding landscape to best create new varieties that meet the demands of the end user.

1 ____ 10

Strongly Disagree Strongly Agree

32. I am able to understand how new knowledge and innovations can best be utilized in my plant breeding program.

1 ____ 10

Strongly Disagree Strongly Agree

33. I am constantly looking at how to better exploit the knowledge that is contained within my breeding program.

1 ____ 10

Strongly Disagree Strongly Agree

34. I am confident that the technologies and methods I use within my breeding program yield the best possible results.

1 ____ 10

Strongly Disagree Strongly Agree

35. Using newly acquired knowledge and innovations always leads to increased genetic gain within the breeding program.

1 ____ 10

Strongly Disagree Strongly Agree

36. Using newly acquired knowledge and innovations always leads to increased economic efficiency within the breeding program.

1 ____ 10

Strongly Disagree Strongly Agree

37. Using the space below, please list the academic journals and publications that you read in order of importance to your breeding activities and indicate typical frequency with a check mark.

________________________________ __ Weekly __Monthly __Annually

________________________________ __ Weekly __Monthly __Annually

________________________________ __ Weekly __Monthly __Annually

________________________________ __ Weekly __Monthly __Annually

________________________________ __ Weekly __Monthly __Annually

________________________________ __ Weekly __Monthly __Annually

Section 4 – Molecular Markers – MAS

Using the following table and the space provided below please indicate the following: Within the following categories, what markers are you currently using and for what classification of wheat are you using them for? When did you began using said marker(s)? When did you become aware of said marker(s)? As well mark yes or no, if believe the marker(s) associated with that trait to be reliable, as well as indicate a percentage on how reliable you deem it to be.

***Note: If you are currently using a marker/markers that are not listed below in one of the categories, use the space beneath the table to identify said marker(s), when you began using said marker(s), what classification you are using said markers for, and when you became aware of said marker(s). As well mark yes or no, if you believe the marker(s) associated with that trait to be reliable, as well as indicate a percentage on how reliable you deem it to be.**

EXAMPLE:

MARKER TRAIT	USED (Y/N, Wheat Classification)	1st YEAR USED	AWARENESS YEAR	RELIABILITY (Y/N, and %)
Leaf rust resistance	Y, CWAD	2011	2007	Y, 100%
Dwarfing genes	N	N/A	2000	N, 30%

MARKER TRAIT	USED (Y/N, Wheat Classification)	1st YEAR USED	AWARENESS YEAR	RELIABILITY (Y/N, and %)
Leaf rust resistance				

MARKER TRAIT	USED (Y/N, Wheat Classification)	1st YEAR USED	AWARENESS YEAR	RELIABILITY (Y/N, and %)
Stripe rust resistance				
Stem rust resistance				
Combined rust resistance				
Powdery mildew Resistance				
Fusarium head blight resistance				
Eyespot, septoria tritici blotch, toxin tolerance				
Hessian fly resistance				
Russian wheat aphid resistance				
Wheat stem sawfly resistance				
Greenbug resistance				
Wheat streak mosaic virus resistance				
Barley yellow dwarf virus resistance				

MARKER TRAIT	USED (Y/N, Wheat Classification)	1st YEAR USED	AWARENESS YEAR	RELIABILITY (Y/N, and %)
Soil-borne wheat mosaic virus resistance				
High grain protein content gene				
Thousand grain weight – grain size gene				
Pre harvest sprouting tolerance				
Gluten strength				
Grain texture				
Semolina texture				
Reduced grain cadmium concentration				
Starchy proteins: waxy mutants				
Aluminum tolerance				
Drought tolerance and rootbiomass				
Dwarfing genes				
Vernalization				

MARKER TRAIT	**USED (Y/N, Wheat Classification)**	**1st YEAR USED**	**AWARENESS YEAR**	**RELIABILITY (Y/N, and %)**

38. During your time as a breeder, have you changed technologies or practices for breeding? __Yes __No. (Follow up ---Please explain why or why not)

39. In conclusion, why or why not do you currently utilize MAS in your wheat breeding program?

40. In your opinion what are the most important factors that currently limit the use of MAS in your program?

41. In your opinion, what are the most important factors that currently limit the use of MAS in Canadian wheat breeding in general?

42. In your opinion is genomic selection (GS) ever going to be used as the primary method for breeding wheat?

Appendix B

Trait Level Adoption and Awareness Curves

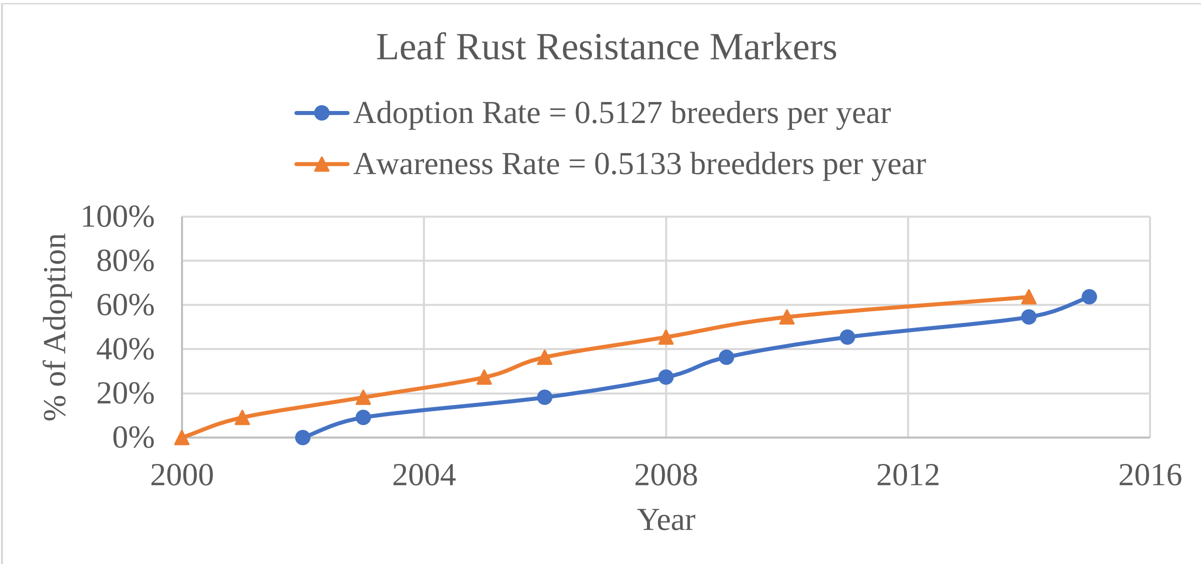

Figure B.1 Industry Leaf Rust Resistance Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

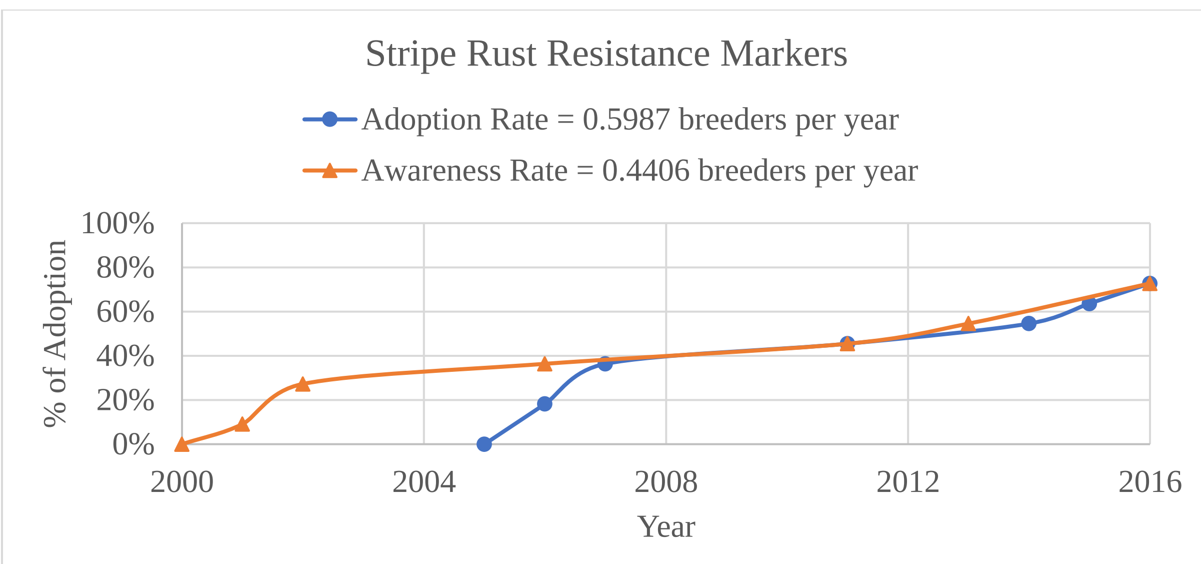

Figure B.2 Industry Stripe Rust Resistance Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

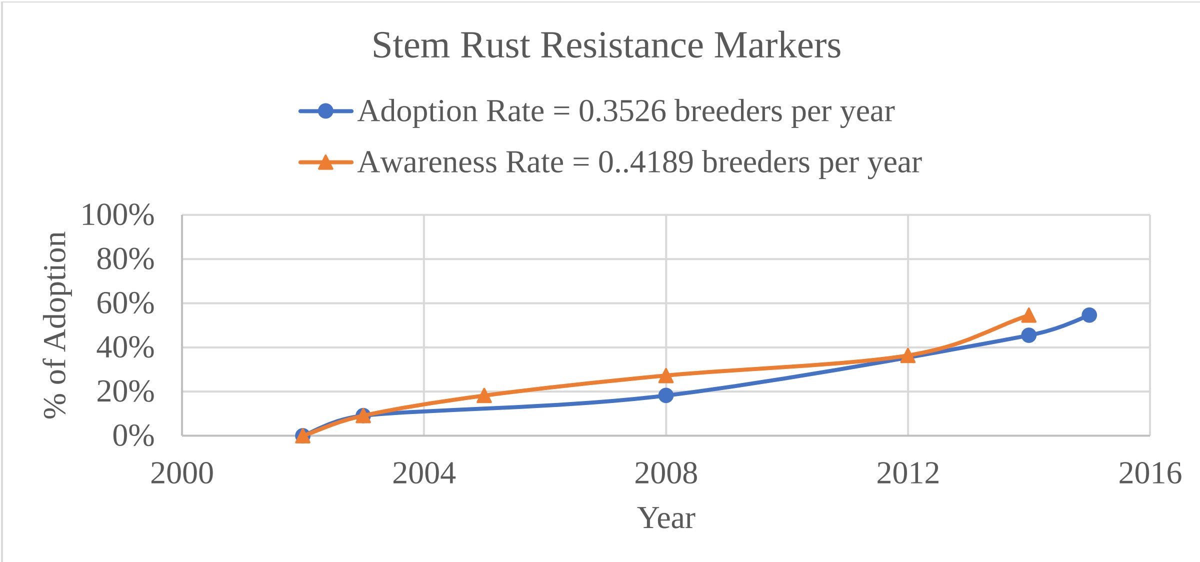

Figure B.3 Industry Stem Rust Resistance Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

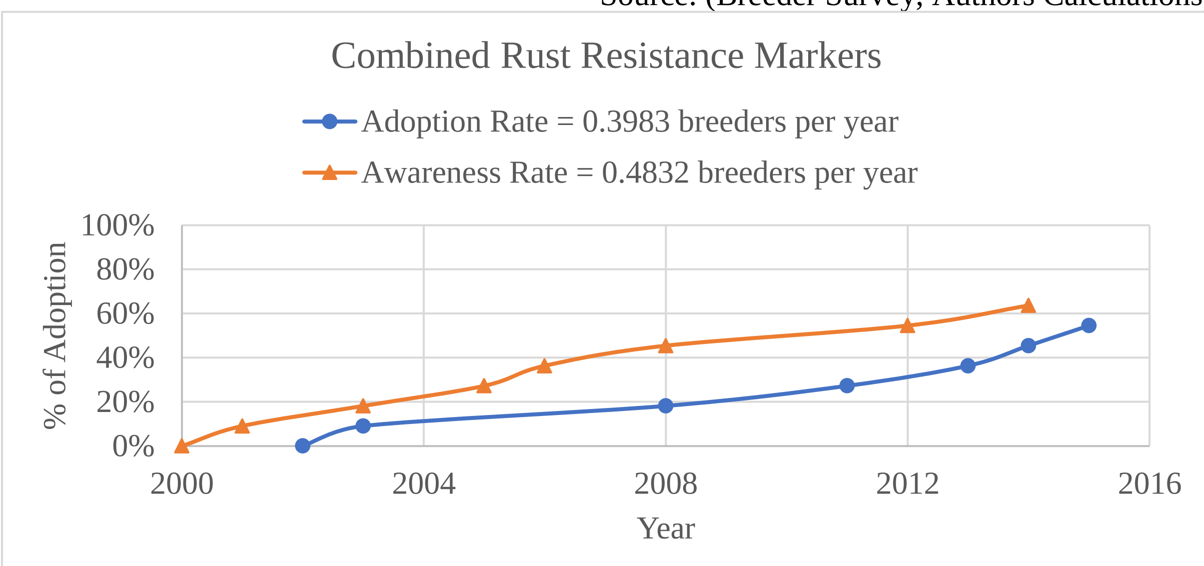

Figure B.4 Industry Combined Rust Resistance Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

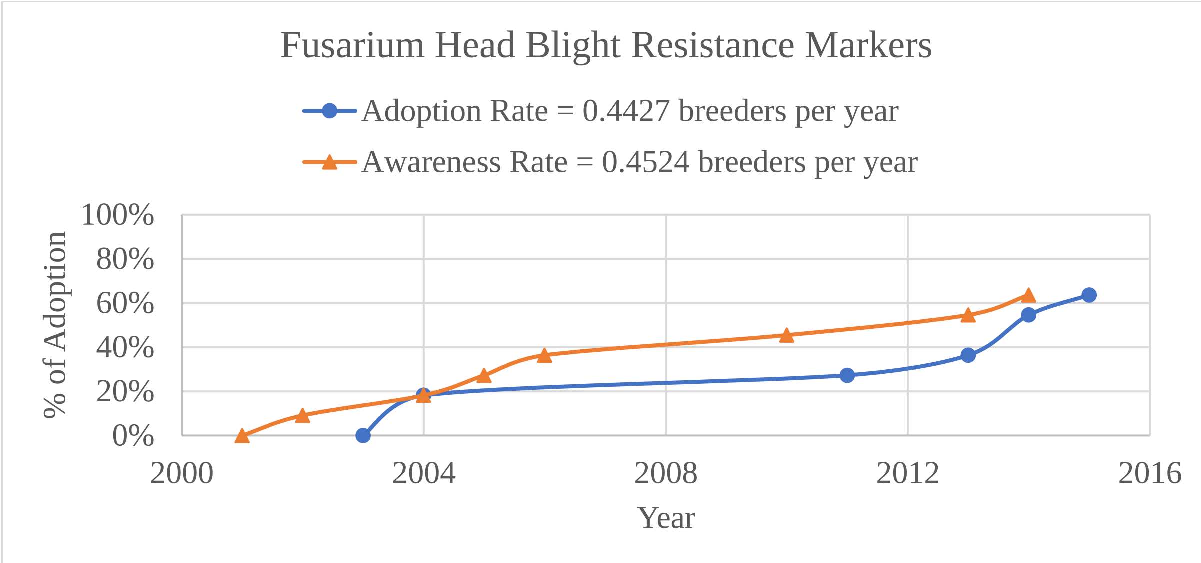

Figure B.5 Industry Fusarium Head Blight Resistance Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

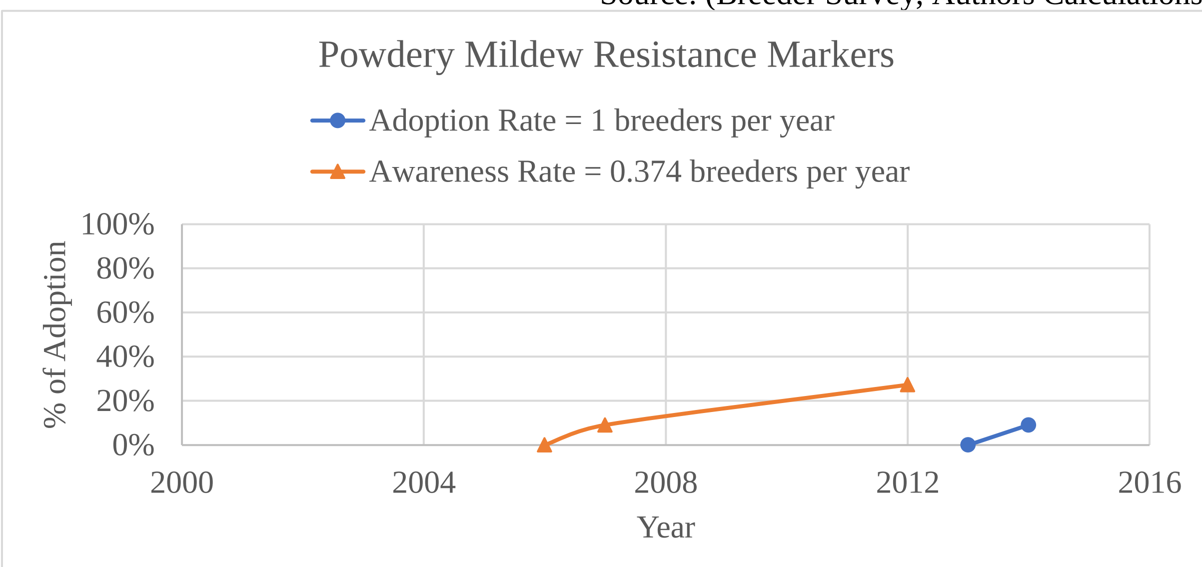

Figure B.6 Industry Powdery Mildew Resistance Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

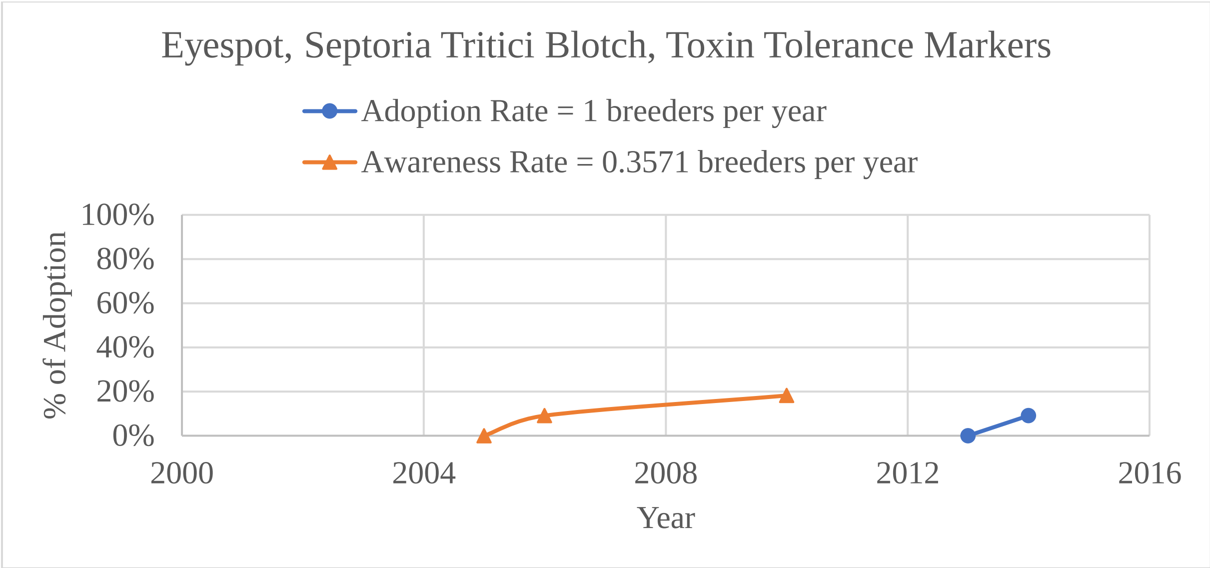

Figure B.7 Industry Eyespot, Septoria Tritici Blotch, Toxin Tolerance Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

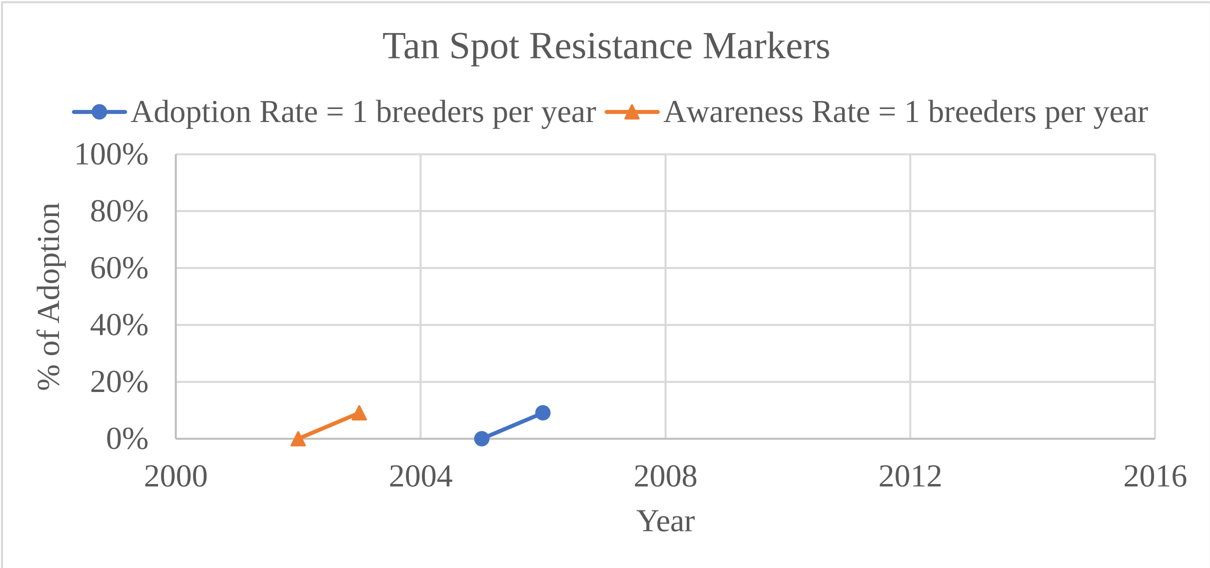

Figure B.8 Industry Tan Spot Resistance Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

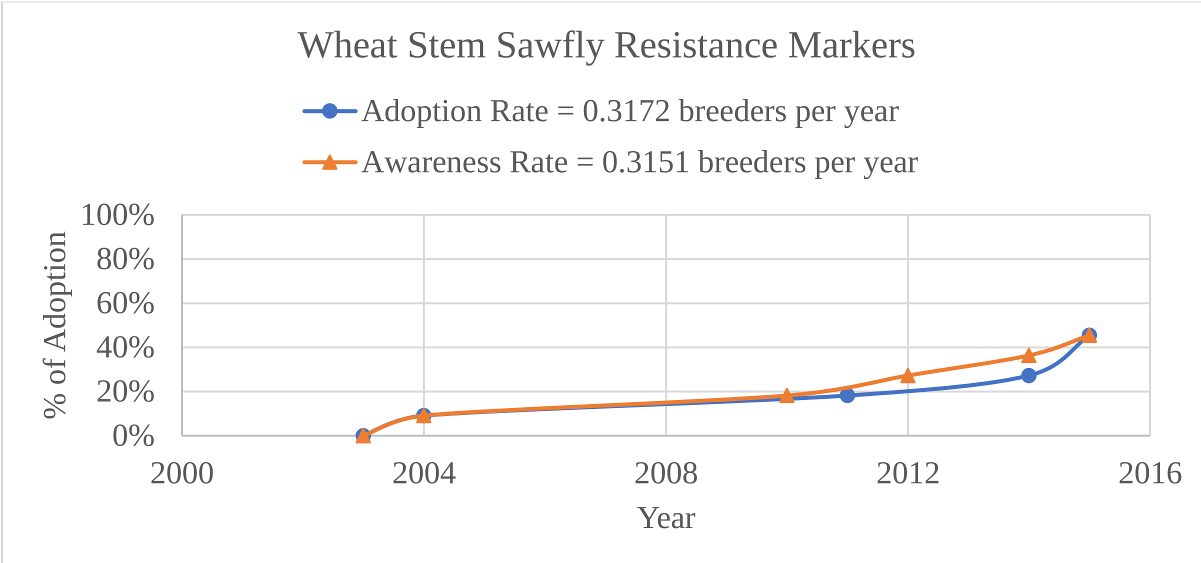

Figure B.9 Industry Wheat Stem Sawfly Resistance Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

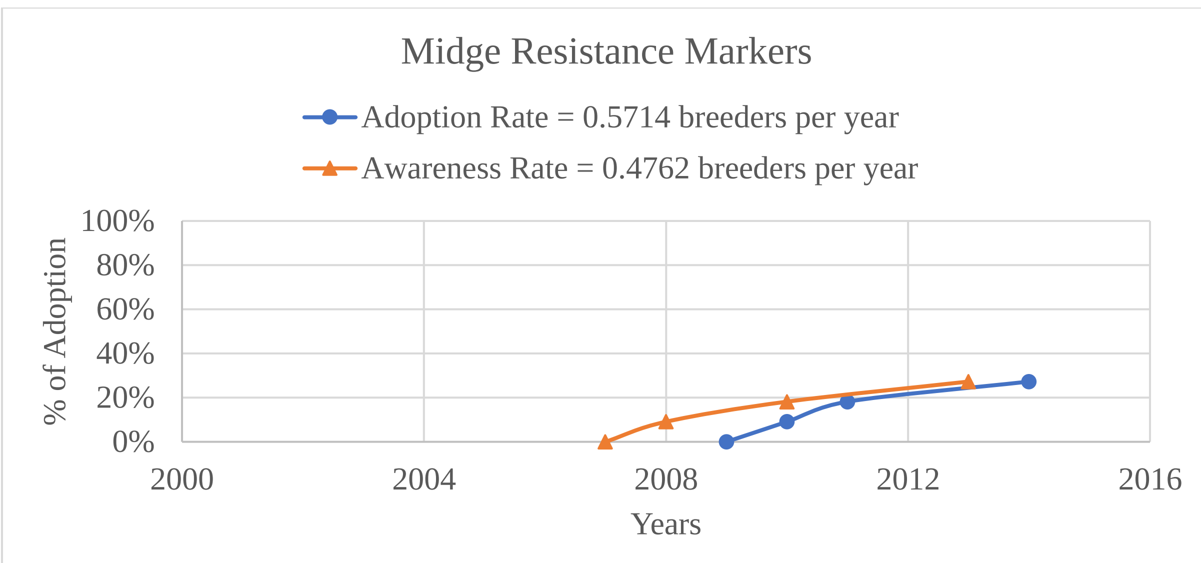

Figure B.10 Industry Midge Resistance Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

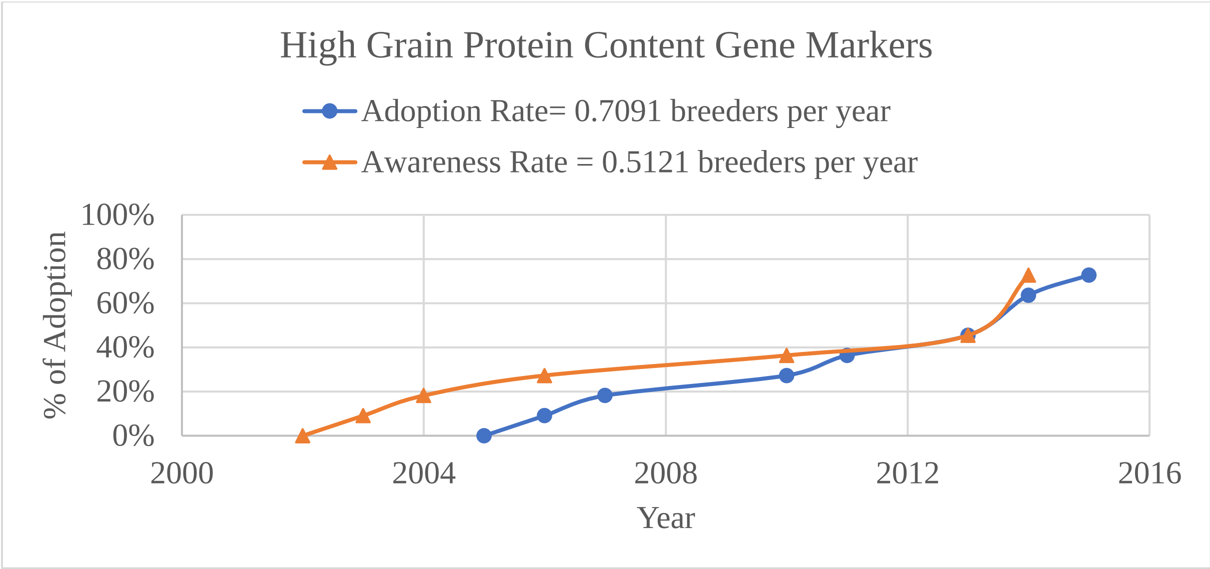

Figure B.11 Industry High Grain Protein Content Gene Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

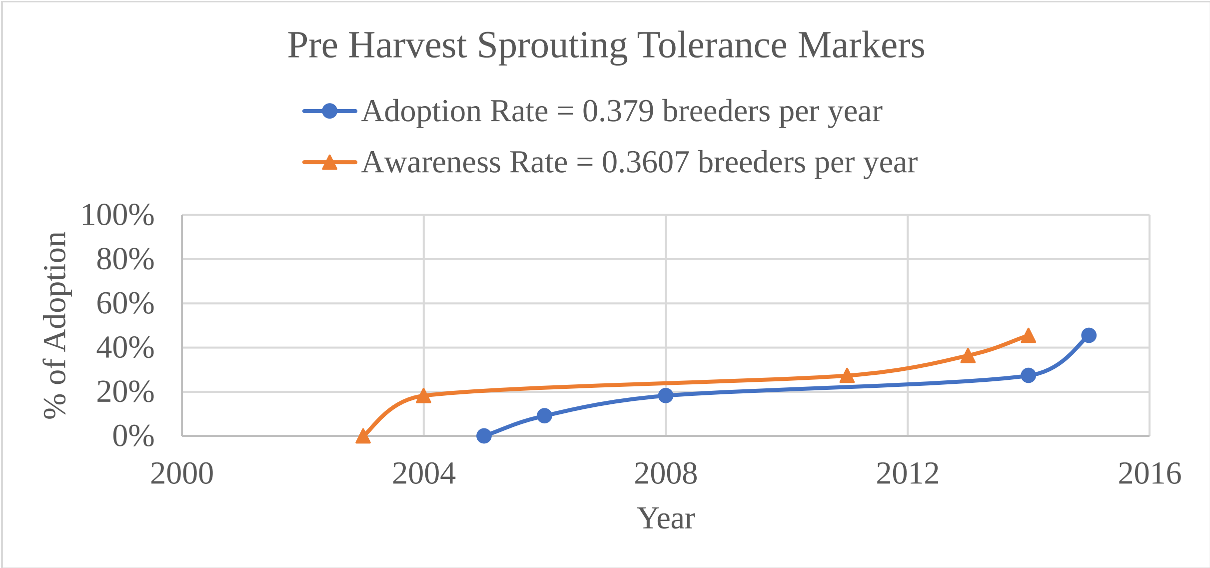

Figure B.12 Industry Pre Harvest Sprouting Tolerance Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

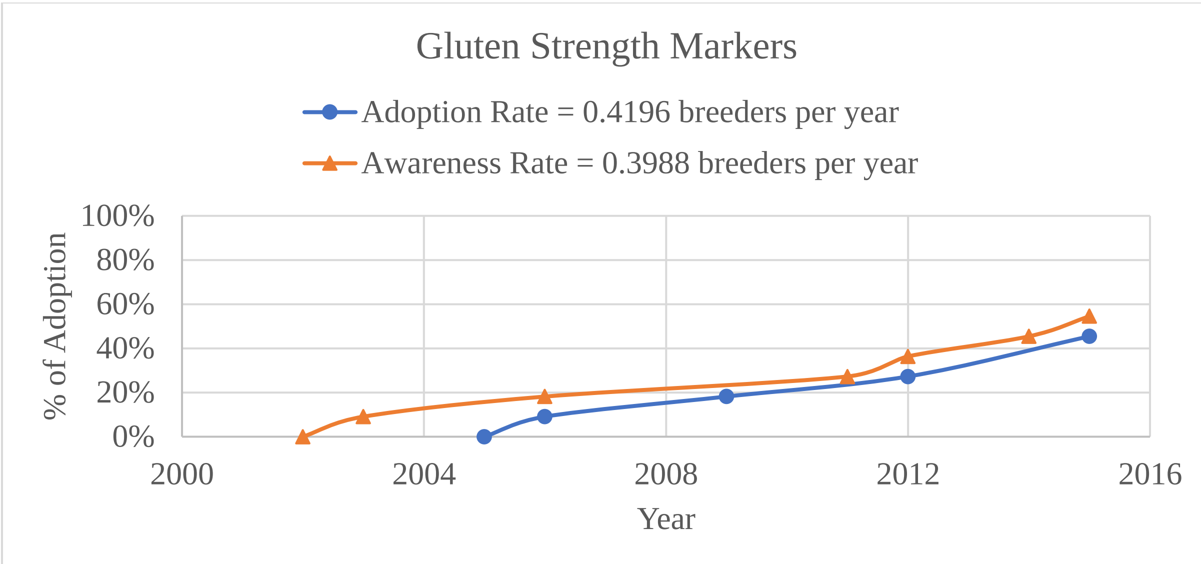

Figure B.13 Industry Gluten Strength Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

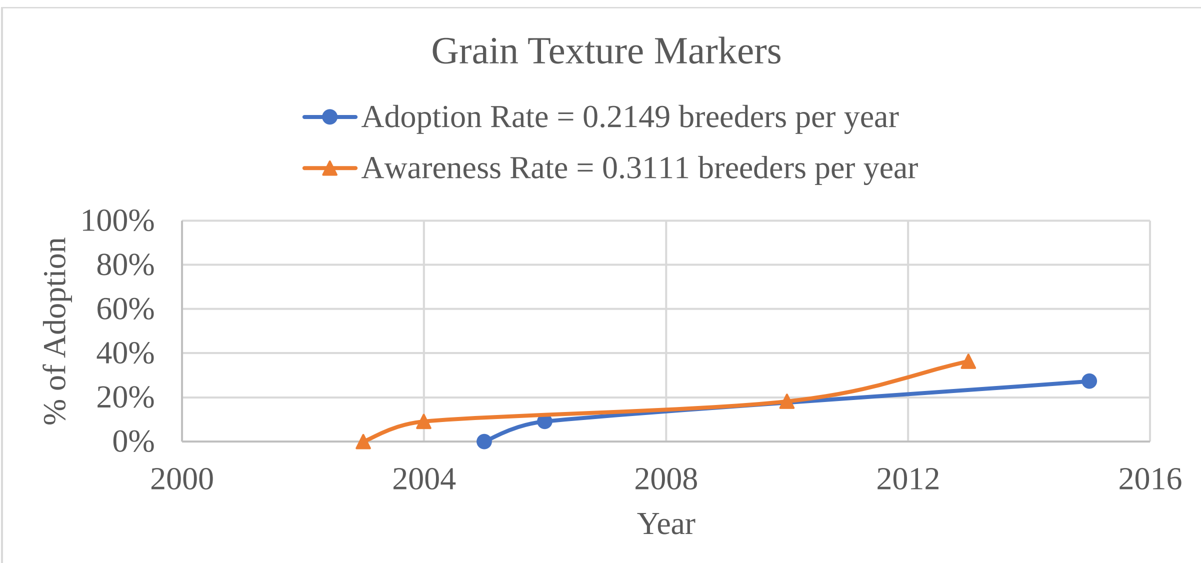

Figure B.14 Industry Grain Texture Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

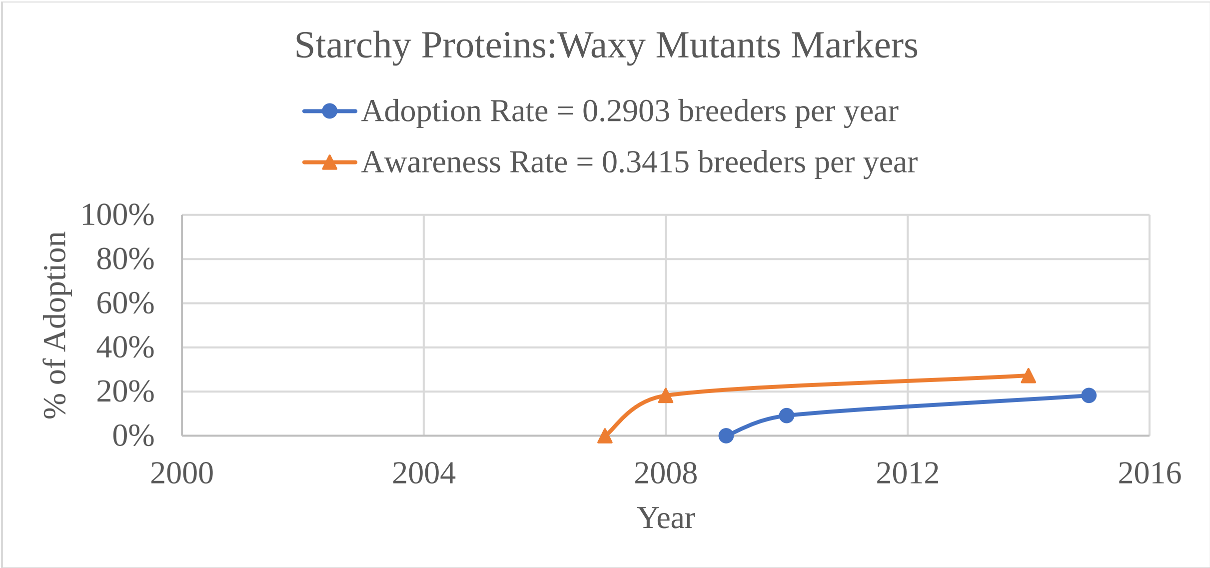

Figure B.15 Industry Starchy Proteins: Waxy Mutants Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

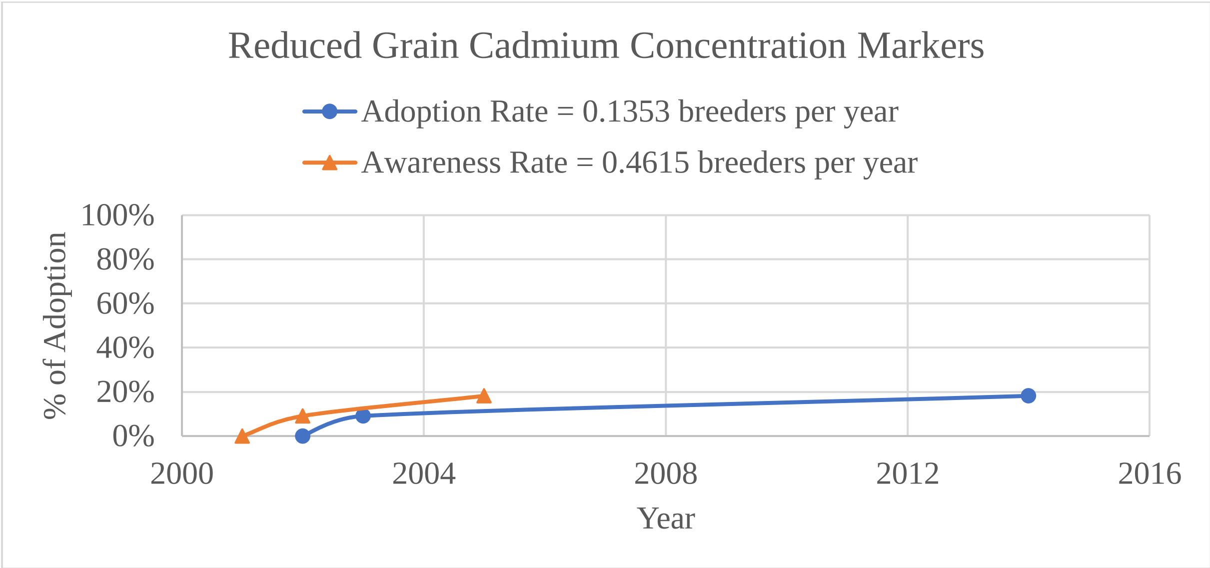

Figure B.16 Industry Reduced Grain Cadmium Concentration Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

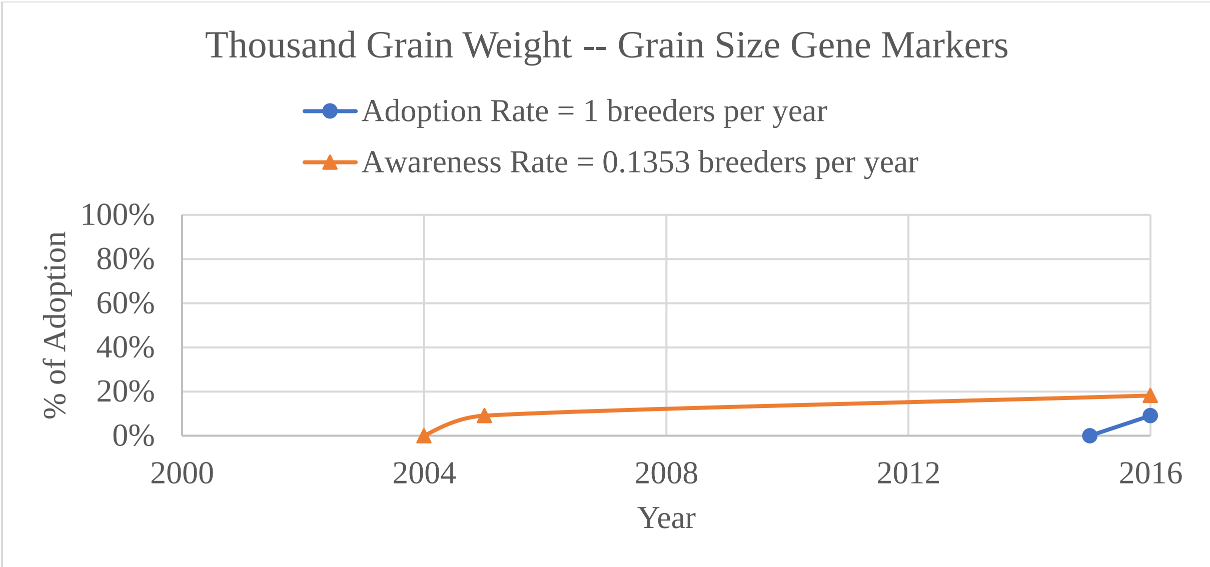

Figure B.17 Industry Thousand Grain Weight – Grain Size Gene Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations

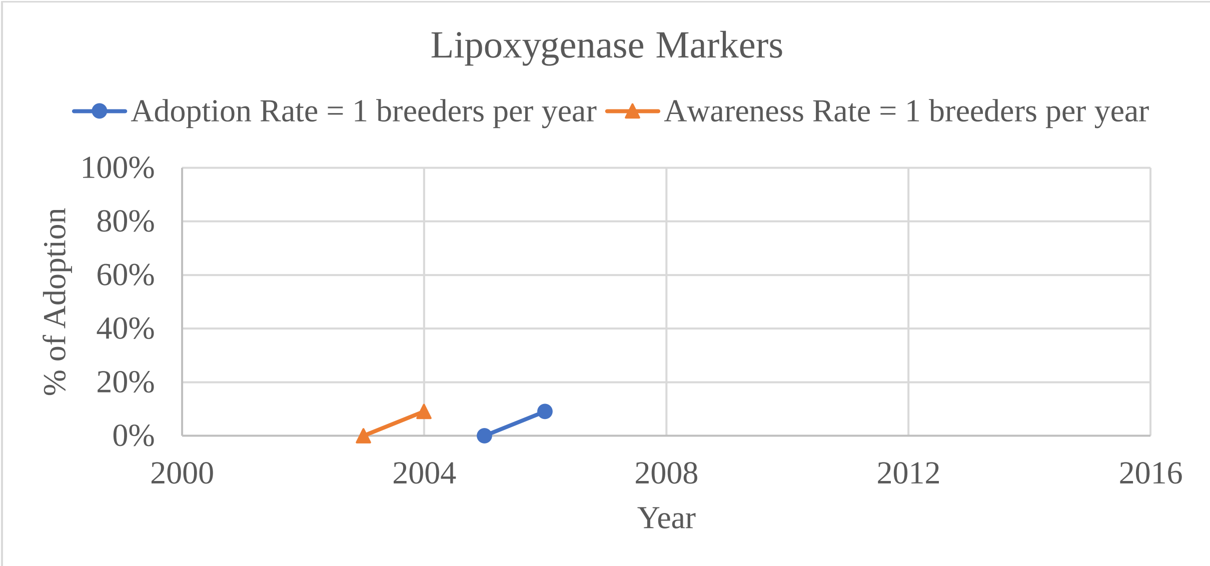

Figure B.18 Industry Lipoxygenase Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

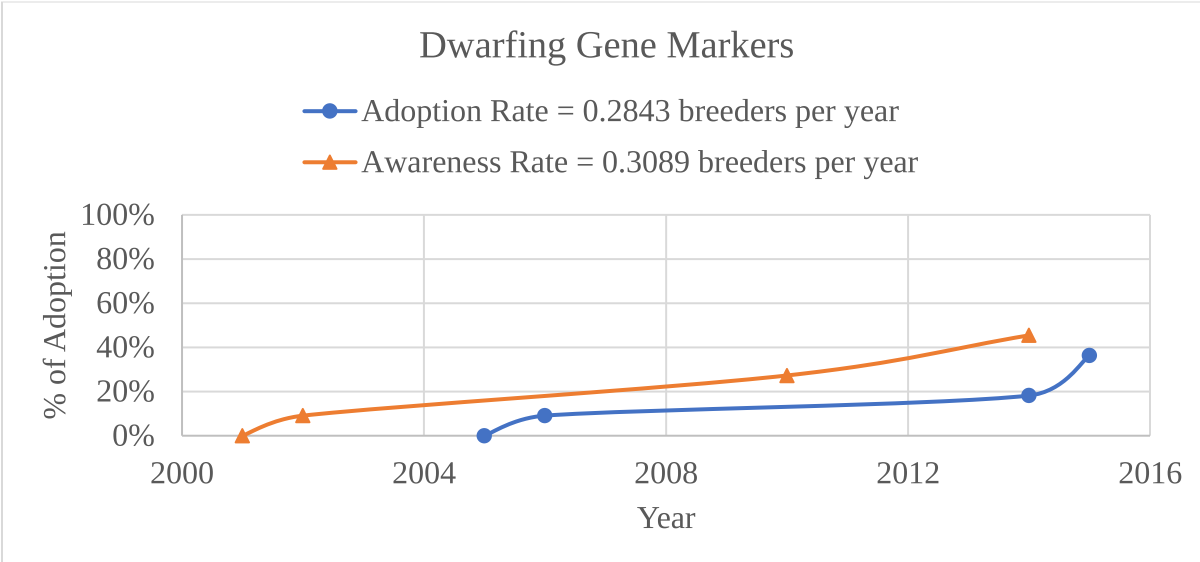

Figure B.19 Industry Dwarfing Gene Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

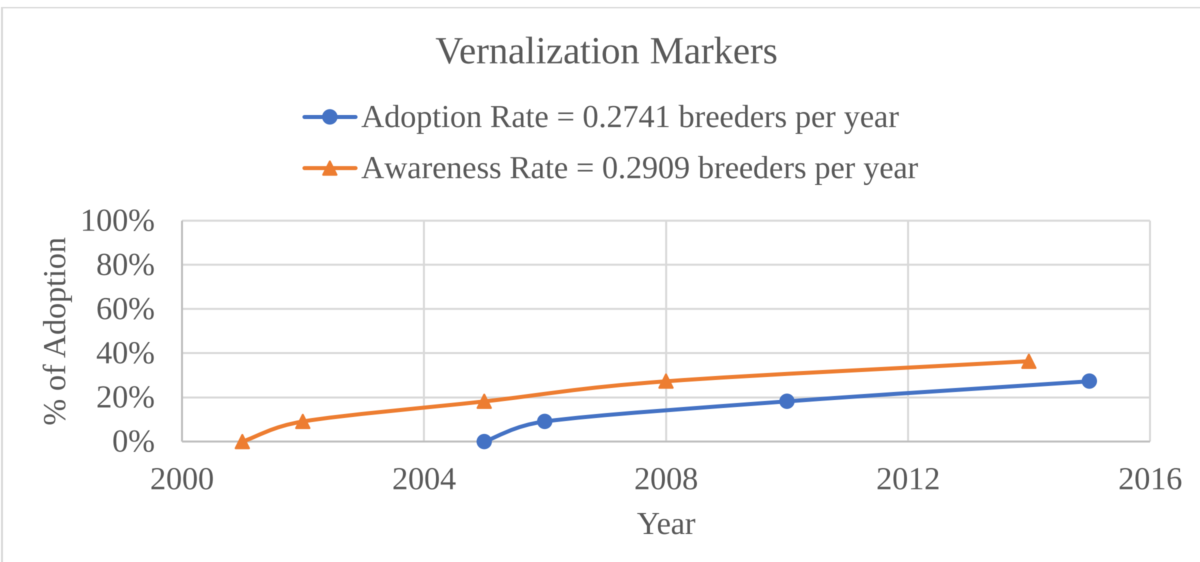

Figure B.20 Industry Vernalization Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

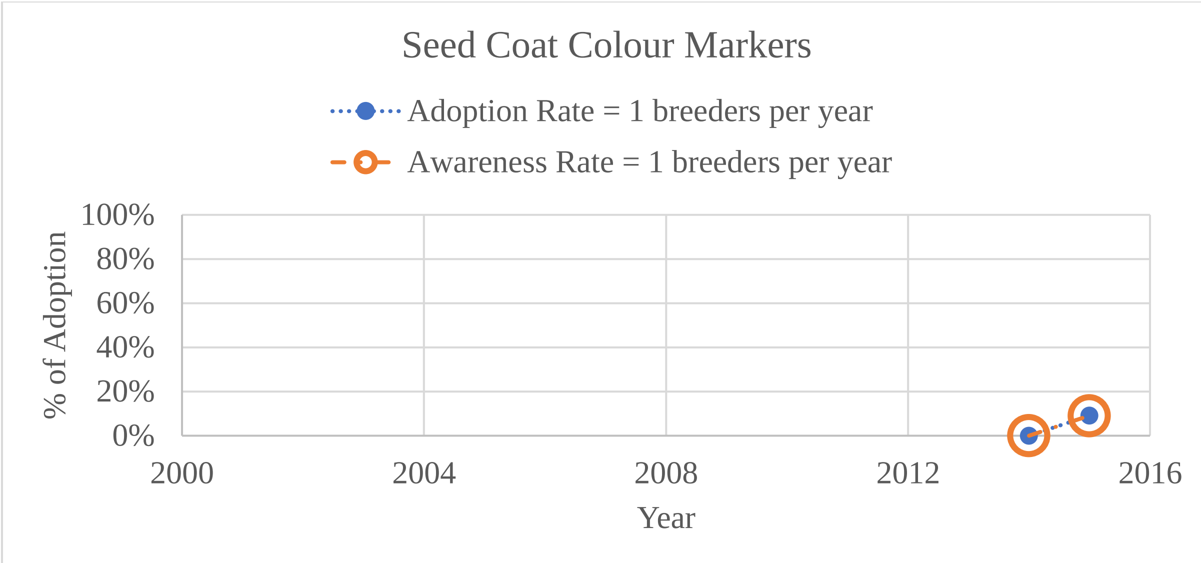

Figure B.21 Industry Seed Coat Colour Adoption and Awareness Curves

Source: (Breeder Survey, Authors Calculations)

Appendix C

Perceived Reliability of Makers

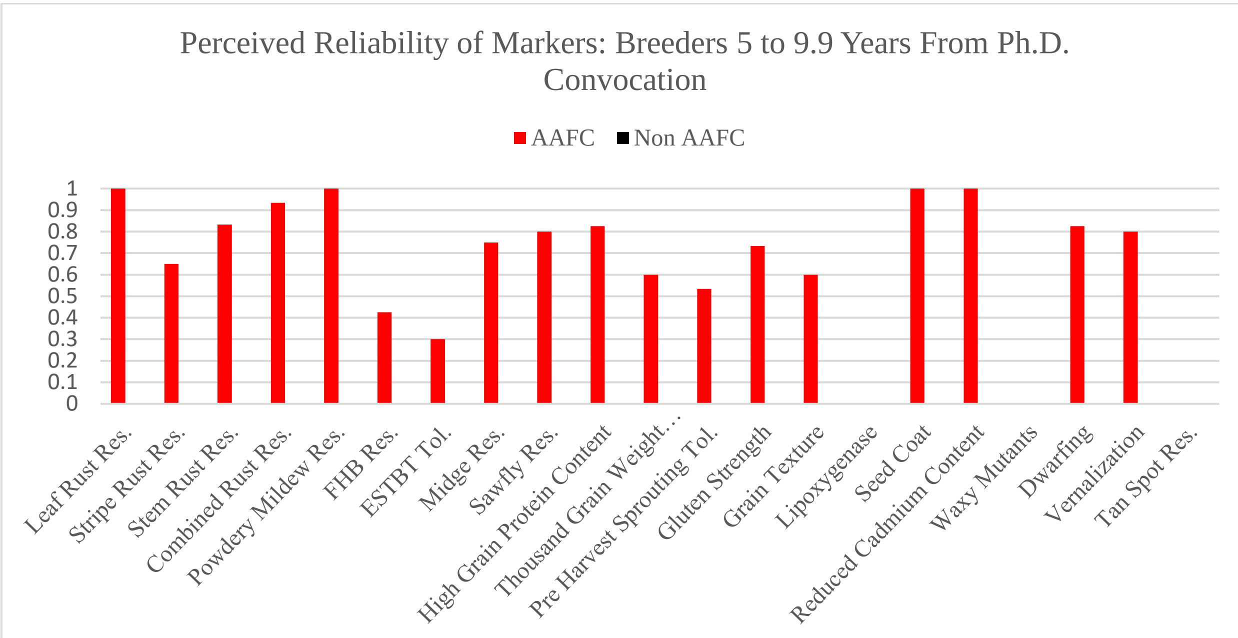

Figure C.1 Perceived Reliability of Markers: Breeders 5 to 9.9 Years From Ph.D. Convocation

Source: (Breeder Survey, Authors Calculations)

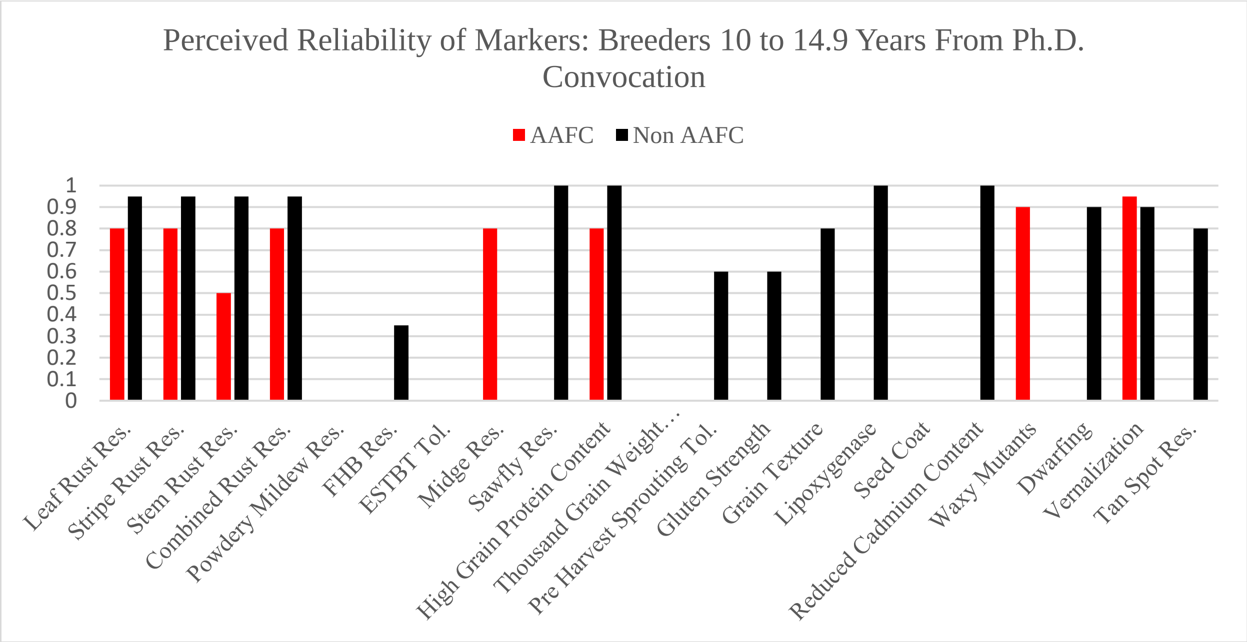

Figure C.2 Perceived Reliability of Markers: Breeders 10 to 14.9 Years From Ph.D. Convocation

Source: (Breeder Survey, Authors Calculations)

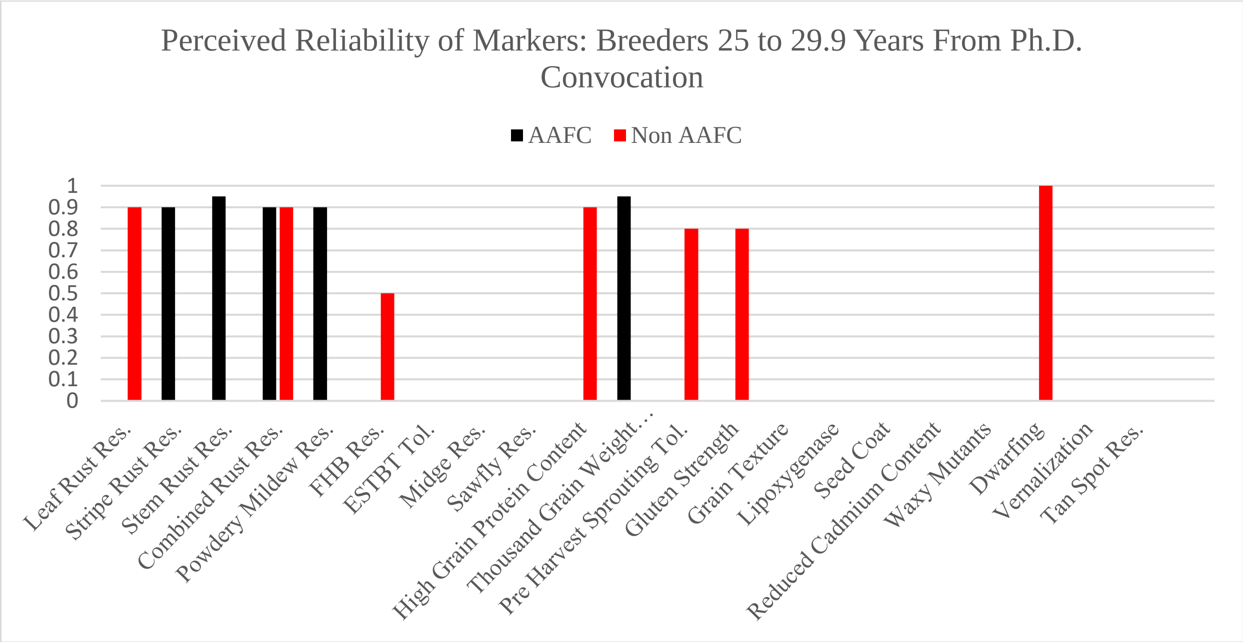

Figure C.3 Perceived Reliability of Markers: Breeders 25 to 29.9 Years From Ph.D. Convocation

Source: (Breeder Survey, Authors Calculations)

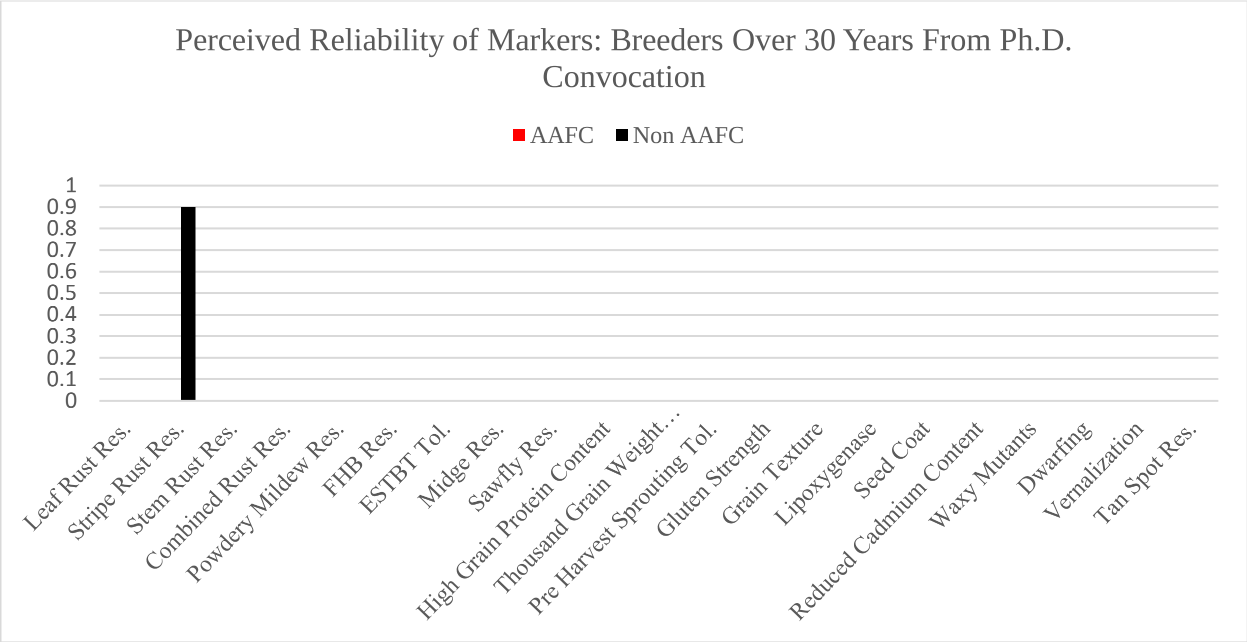

Figure C.4 Perceived Reliability of Markers: Breeders Over 30 Years From Ph.D. Convocation

Source: (Breeder Survey, Authors Calculations)

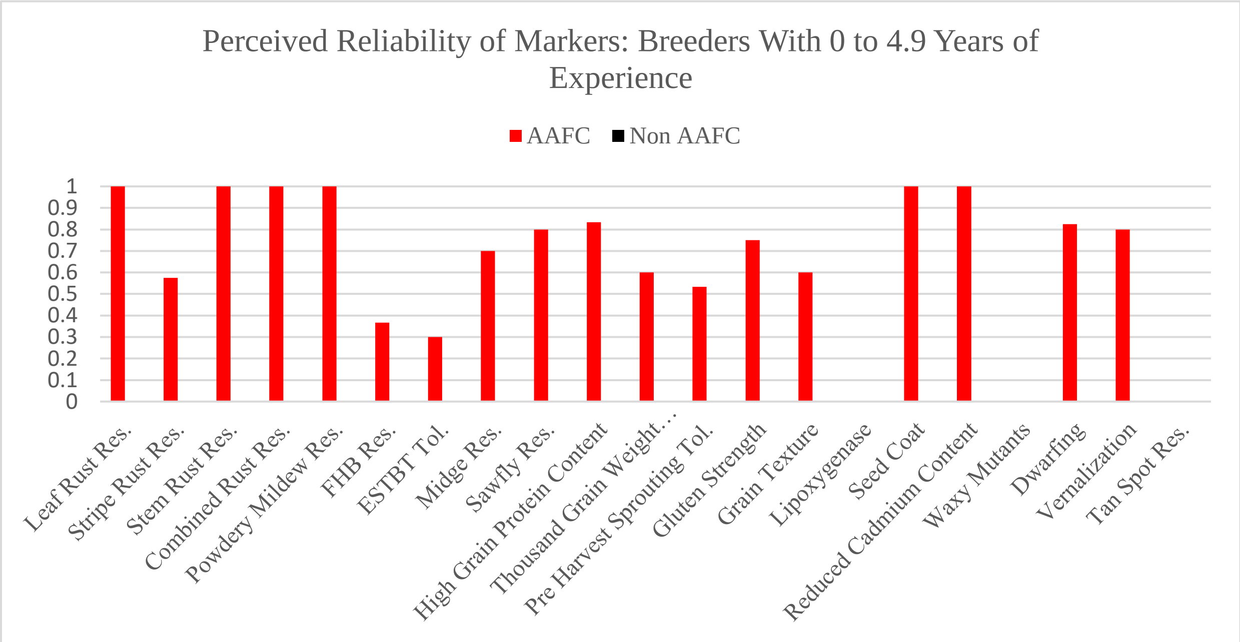

Figure C.5 Perceived Reliability of Markers: Breeders With 0 to 4.9 Years of Experience

Source: (Breeder Survey, Authors Calculations)

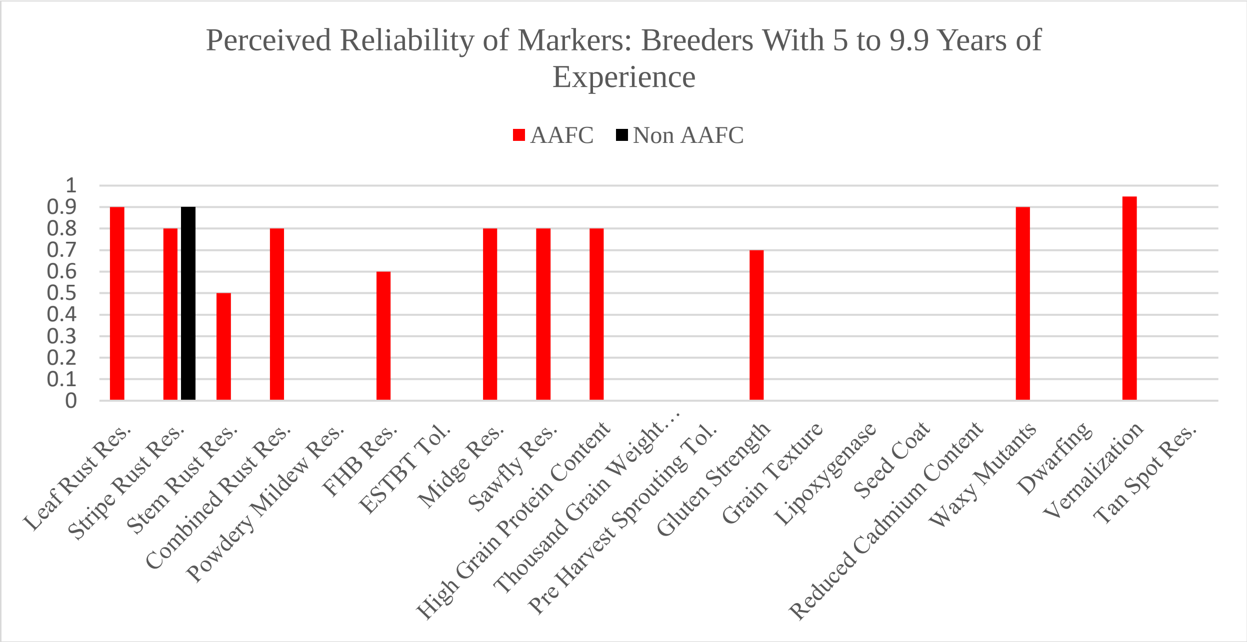

Figure C.6 Perceived Reliability of Markers: Breeders With 5 to 9.9 Years of Experience

Source: (Breeder Survey, Authors Calculations)

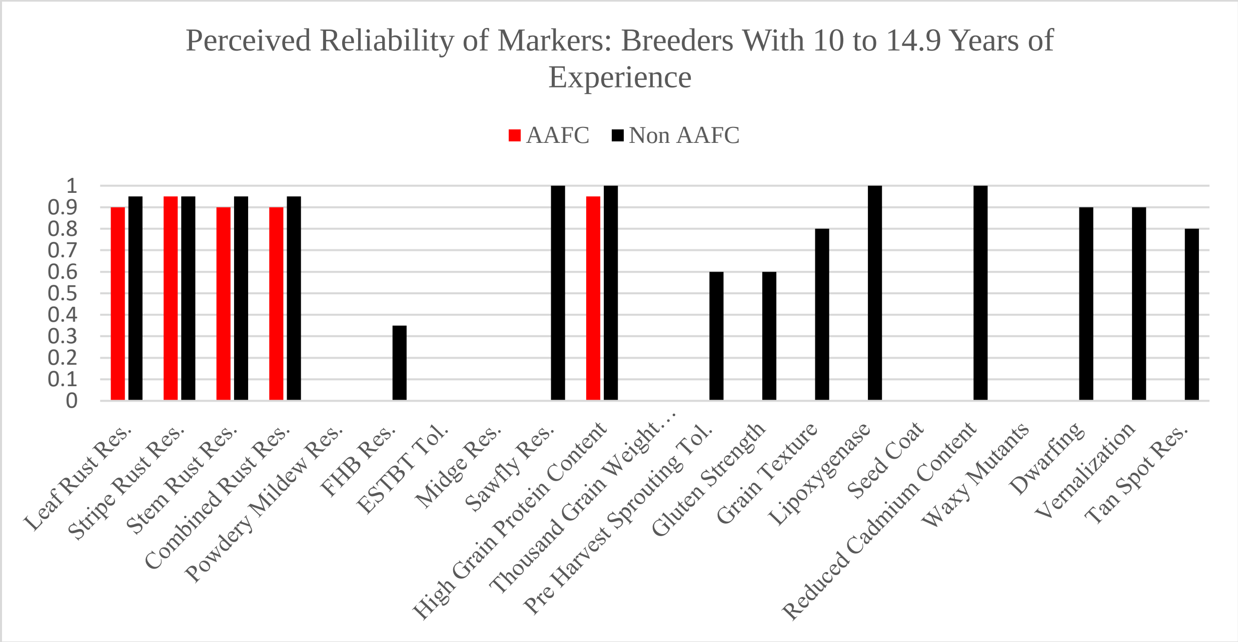

Figure C.7 Perceived Reliability of Markers: Breeders With 10 to 14.9 Years of Experience

Source: (Breeder Survey, Authors Calculations)

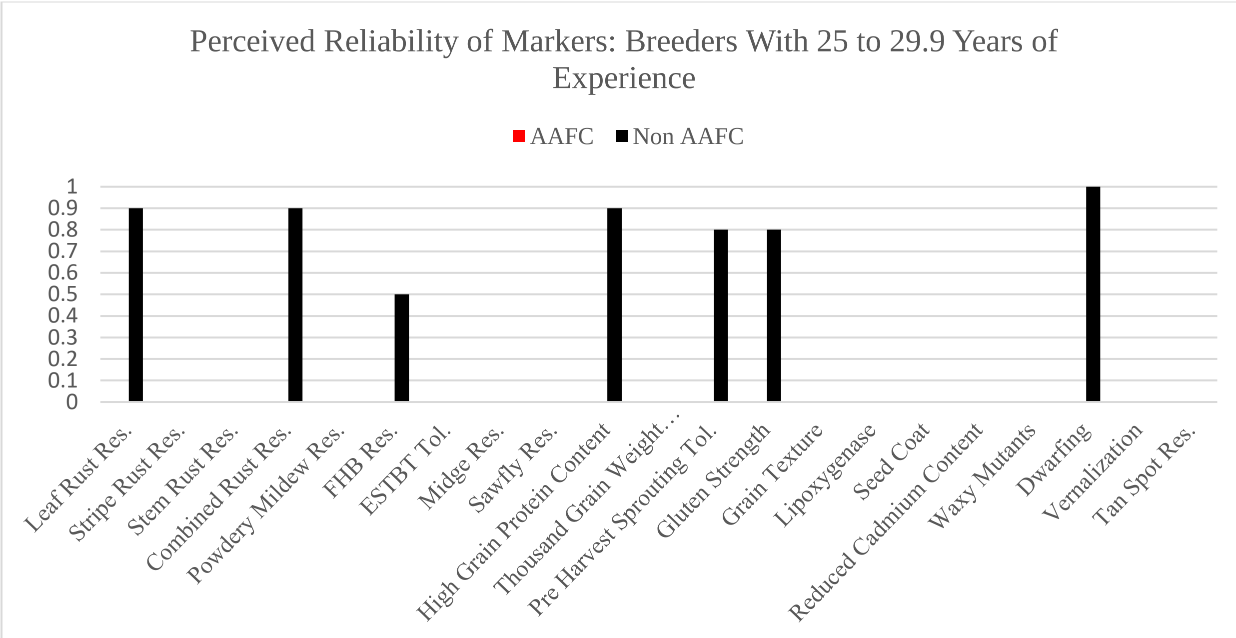

Figure C.8 Perceived Reliability of Markers: Breeders With 25 to 29.9 Years of Experience

Source: (Breeder Survey, Authors Calculations)

Appendix D

Trait Level Adoption Lags

Table D.1 Trait Level Adoption Lags: AAFC and Non-AAFC

Individual Marker Trait Category	AAFC Breeder - Average Adopt Lag in Years	Non - AAFC Breeder - Average Adopt Lag in Years
Leaf Rust Resistance	2.36	5
Stripe Rust Resistance	2.75	4.25
Stem Rust Resistance	2	N/A*
Combined Rust Resistance	3	12
FHB Resistance	2.1667	2
Powdery Mildew Resistance	2	N/A
ESTBT Tolerance	N/A*	N/A
Tan Spot Resistance	N/A	3
Wheat Stem Sawfly Resistance	0.5	1.5
Midge Resistance	1.67	N/A
High Grain Protein Content Gene	1	3
Pre Harvest Sprouting Tolerance	1.33	3
Gluten Strength	0.8	3
Grain Texture	2	2
Starchy Proteins: Waxy Mutants	1.33	N/A
Reduced Grain Cadmium Concentration	N/A*	1
Thousand Grain Weight - - Grain Size Gene	0	N/A
Lipoxygenase	N/A	2
Seed Coat Color	0	N/A
Dwarfing Genes	.333	4.5
Vernalization	1.67	4
Disease	2.48	5.54
Insect	1.2	1.5
Improved Agronomics	1.03	3.19
All	1.79	3.59
*Omitted (Awareness Data Missing)		

Source: (Breeder Survey, Authors Calculations)

Appendix E

The Experience Effect

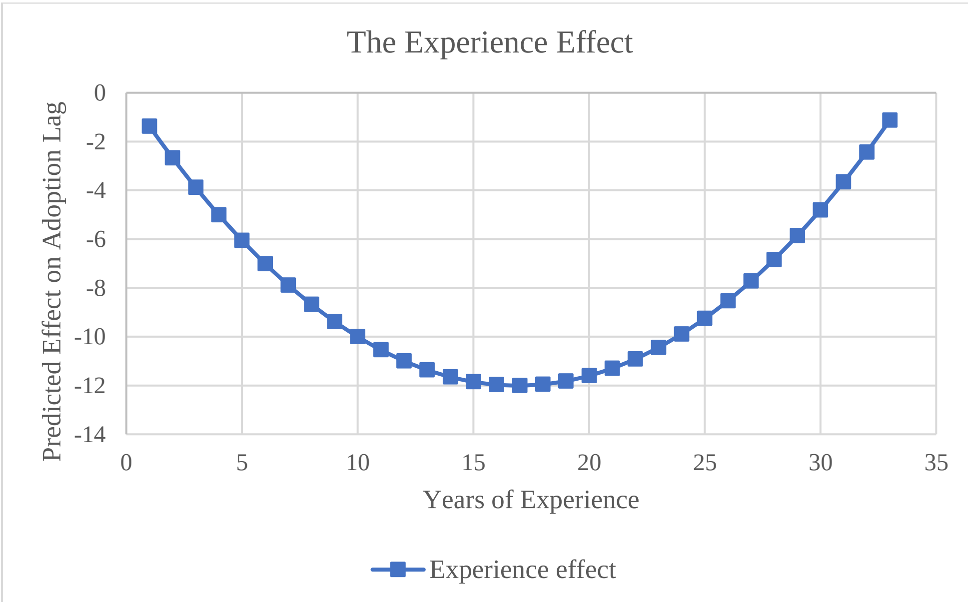

Figure E.1 The Experience Effect
Source: (Breeder Survey, Authors Calculations)

Appendix F

Supplementary Tables

Table F.1 Number of Parental Lines Used and Initial Crosses Made

	Number of Parental Lines Used Per Year*	Number of Parental Lines Used Per Year Known to Have Desired Markers*	Number of Initial Cross Made Per Year / Cycle*
Average	117.13	38.56	38.43
Median	32.5	20	25
Range	3 - 1320	0 - 360	3 - 150
*Incomplete Data			

Source: (Breeder Survey, Authors Calculations)

Table F.2 Affordability of MAS

	Dollar Per Line Cost of MAS*	MAS Budget Per Program Cost*
Average	$15.35	$60,215.22
Median	$5	$30,000
Range	$1.63 - $200	$2,500 - $300000
*Incomplete Data		

Source: (Breeder Survey, Authors Calculations)

Table F.3 Breeder Journal Consumption and Rankings

Academic Journal Read by Breeder	Number of Breeders Per Period				Breeder Ranking*
	Weekly	Monthly	Annually	Unspecified	
Canadian Journal of Plant Science	1	7	1	0	1
Crop Science	1	6	1	0	2
Theoretical and Applied Genetics	1	3	2	0	3
Plant Breeding	0	3	2	0	4
Euphytica	0	2	2	0	5
Molecular Breeding	0	1	1	1	6
Public Library of Science	0	2	0	1	7
Canadian Journal of Plant Pathology	0	1	2	0	8
Nature	1	0	1	0	9
Nature Genetics	0	2	0	0	10
Science	1	1	0	0	11
Molecular and General Genetics	0	1	1	0	12
Cereal Chemistry	0	1	1	0	13
Plant Pathology	0	1	2	0	14
Proceedings of the National Academy of Science of the United States of America	0	1	0	0	15
Google Scholar	1	0	0	0	16
Journal of Plant Registrations	0	1	1	0	17
Plant Physiology	0	1	0	0	18
Top Crop Manager	0	1	0	0	19
Molecular Plant-Microbe Interactions	0	1	0	0	20
Plant Disease	0	0	1	0	21
European Journal of Plant Pathology	0	0	1	0	22

*Breeders ranked journals from most important to least important (1 = most, 22 = least)

Source: (Breeder Survey, Authors Calculations)