A DOUBLED HAPLOID LABORATORY FOR KANSAS WHEAT BREEDING:
AN ECONOMIC ANALYSIS OF BIOTECHNOLOGY ADOPTION

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Andrew Barkley
Department of Agricultural Economics
Kansas State University

Forrest G. Chumley
Heartland Plant Innovations
Manhattan, Kansas
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0.1 AUTHOR INFORMATION

Andrew Barkley
Professor and University Distinguished Teaching Scholar
Department of Agricultural Economics
Kansas State University
217 Waters Hall
Kansas State University
Manhattan, KS 66506-4011
Phone: 785-477-1174
Fax: 785-532-6925
Email: barkley@ksu.edu

Forrest G. Chumley
President and CEO
Heartland Plant Innovations, Inc.
217 Southwind Place
Manhattan, KS 66503
Phone: 785-539-0255
Fax: 785-539-8946
Email: fchumley@heartlandinnovations.com
0.3 EXECUTIVE SUMMARY

This report provides an assessment and evaluation of the use of doubled haploid lines (DHs) to accelerate breeding and gene discovery in wheat breeding. The report includes a quantitative assessment and references to the relevant literature. The research project addresses three key points:

✓ Overview of traditional breeding methods such as pedigree selection or bulk selection, comparing these methods to selection schemes that emphasize production and analysis of doubled haploid lines.

✓ Economic impact of using doubled haploid lines to deliver new wheat varieties

✓ Economic benefits of selecting from smaller populations, and improved efficiency of selection using doubled haploid lines.

Interviews with wheat breeders provided quantitative calibration of the major effects of a doubled haploid laboratory. The interviewed wheat breeders confirmed two major advantages to doubled haploid (DH) technology: (1) greatly accelerated time to market for new wheat varieties, and (2) faster genetic gains in wheat yields. An economic model was built based on previous literature, knowledge of the wheat industry, and information gleaned from the wheat breeder interviews. A baseline scenario was estimated for the most likely set of conditions facing the future of the introduction of a doubled haploid laboratory into the Great Plains wheat breeding industry.

The estimated results of the baseline case provided evidence that both of the advantages of DH methods listed above would provide truly large economic gains to the wheat industry, and to wheat consumers in Kansas, in the United States (US), and throughout the globe. While it can be challenging to forecast the future, the economic evaluation of the doubled haploid laboratory indicated that the large and socially significant returns are robust to the possibility of a wide range of future economic changes, including price and quantity movements in wheat markets.
CHAPTER ONE. INTRODUCTION, BACKGROUND, AND OVERVIEW

In recent years, biotechnology has resulted in large increases in corn and soybean production, through the development of varieties that are resistant to herbicides, diseases, and drought. In 2010, over 90 percent of the acres planted to corn and soybeans in Kansas were varieties produced using biotechnology methods (KAS 2010). Adoption of these varieties, together with increased demand for biofuels, have led to a shift of acreage in the United States (US) out of wheat and into corn and soybeans since 2000 (KAS 2010). Recently, historically high wheat prices resulting from smaller acreages and weather events have resulted in increased interest and investment in wheat variety development by both private firms and public wheat breeders (USDA/ERS 2011). The creation of a new wheat variety is a lengthy and costly process. Traditional methods can require up to 12 years. Economists have noted that any innovation that reduces the variety development time span, or "time to market (TTM)," could have large economic benefits, due to lower costs and earlier adoption of economically significant wheat varieties.

Doubled haploid (DH) technology is a method of using biotechnology to reduce variety development time. Doubled haploids are genetically pure inbred plants, now produced in a single year. Traditional wheat breeding techniques typically require multiple generations of inbreeding to stabilize desired traits, or fix the desired characteristics of higher yield, quality characteristics, disease resistance, or agronomic features into "pure lines" that are eventually released as new varieties. However, even after as many as eight generations of inbreeding, the genetic purity ("homozygosity") of a winter wheat line will be only 99.6%. Doubled haploids allow wheat breeders to stabilize desired traits in a single generation, delivering lines with 100% homozygosity in nine months, and thereby reducing the time required for new variety development by up to five years. Doubled haploid laboratories are currently used in Europe, Canada, and Australia (Bonjean and Angus, 2001), but the technology has generally been underutilized, particularly in the United States.

Recently, Heartland Plant Innovations, a public/private partnership, has made plans for the construction of a doubled haploid laboratory to be used by public and private wheat breeders. This research will analyze the economic impact of the adoption and use of biotechnology in wheat variety development. A careful study of economic costs and benefits of the new laboratory will be conducted, with several measures of financial return estimated. This analysis of the impact of
doubled haploids on wheat markets will be estimated to find the economic benefits and costs to wheat producers and consumers in Kansas, the United States, and the rest of the world.

The use of doubled haploids in wheat variety development is timely, interesting, and important for a number of reasons. First, the potential economic benefits of a shortened variety development process are large. Nalley, Barkley, and Chumley (2008) estimated genetic improvement in Kansas wheat varieties to average 0.206 bushels per acre each year. This corresponds to approximately two to three million U.S. dollars of additional revenues from wheat production in Kansas attributable to wheat breeding programs. Yield increases are permanent and cumulative, so after a short number of years, the economic benefits to higher-yielding wheat varieties are large and significant. Adoption of doubled haploid techniques would boost yields much sooner than conventional methods, resulting in immediate increases in economic benefits and large cumulative financial gains to wheat producers in Kansas and wheat consumers worldwide.

Second, the development and adoption of biotechnology in wheat production is likely to grow rapidly in the near future, and careful description and estimation of the economic impacts is needed to better understand the impact of large, rapid technological advance in wheat (Fuglie and Walker 2001). Third, the economics of the introduction of biotechnology in general, and a doubled haploid laboratory in particular, are timely and important. As new techniques are discovered and implemented, the application of economic principles to the technological change allows for a more rapid and efficient transition out of traditional breeding methods to the use of biotechnology in wheat variety development. It is likely that doubled haploid methods will become more efficient as wheat breeders enhance their use of doubled haploids in wheat breeding programs in the near future.

One major contribution of this study is a detailed description and model of wheat variety development, including careful consideration of the timing and costs of investments in wheat breeding. A standard financial model of discounted future costs and revenues is estimated to accurately forecast three financial measures: (1) the benefit/cost ratio, (2) net present value, and (3) internal rate of return for the construction of the double haploid laboratory. Extensive sensitivity analyses will be conducted to gain a better understanding of the impact of model parameter assumptions. Although the proposed DH laboratory is likely to produce pure line wheat seeds for wheat breeders throughout the United States, the study uses Kansas as the baseline geographical unit of analysis, due to data availability and to provide a conservative estimate of the potential economic impacts of a DH laboratory.

The use of biotechnology in corn and soybeans has become nearly universal, setting the stage for biotechnology in wheat to increase rapidly in the next few years. The economic impact will be large and significant, as it has been in other crops. By quantifying the dollar value of these changes, the magnitude of rapid technological change is revealed, with fascinating results.
The details of doubled haploid technology are particularly interesting. In the most commonly-used method, corn pollen is used to fertilize emasculated wheat florets, resulting in new wheat seeds that are genetically pure and stable, each retaining a unique combination of genes carried on their parents' chromosomes (Laurie and Bennett 1988). A description of this process is illuminating, since it represents a major technological breakthrough in crop production. Learning about this application of biotechnology provides economists and social scientists with a broader knowledge of recent advances in biology and biotechnology and the implications.

Economists will be particularly interested in the efficiency gains provided by the use of doubled haploids in wheat variety development. Not only does the new technique drastically reduce wheat varietal development times, but it allows for economies to scale in selecting promising new varieties, and identifying desirable traits in new wheat varieties.

This chapter has provided a brief introduction and overview to the use of doubled haploids in wheat breeding, together with background information on the research presented here, which aims to measure the economic impact of the development of a new double haploid laboratory for wheat breeders. The next chapter outlines and reviews information on wheat breeding techniques.
CHAPTER TWO. SUMMARY OF WHEAT BREEDING TECHNIQUES

2.1 WHEAT BREEDING OVERVIEW

Wheat is a grass that was originally grown in Mesopotamia, and has been cultivated by humans for 10,000 years. Wheat breeding has been practiced for millennia, as summarized by Baenziger and DePauw (2009). Acquaah (2007) provided an excellent overview of the history of plant breeding and genetics. Following Baenziger and DePauw (2009), this overview will discuss five methods of wheat breeding: (1) pedigree selection, (2) bulk selection, (3) single-seed descent, (4) doubled haploid (DH), and (5) the backcross method. These methods are described in greater scientific detail in Baenziger et al. (2009). Shariatpanahi, et al. (2006) concluded that wheat's "Incredible range of adaptation worldwide reflects diversity of genes for adaptation that has been concentrated by breeders over the past 150 years, although improvement work has gone on for millennia."

Baenziger and DePauw (2009) summarized wheat breeding methods, and concluded, "Each method has its advantages and disadvantages. Wheat breeding is remarkably flexible, and these methods are often combined in practice to take advantage of their strengths and the selection environments that occur during cultivar development" (p. 275). Wheat breeding is both a public and private sector activity, becoming more private over time. It should be emphasized that wheat breeders are best served by using a variety of breeding methods.

"We do not expect DH production to replace traditional breeding methods; rather it will provide greater efficiency and new options" (Forster and Thomas, 2005, p. 80).
Specifically, several wheat breeders interviewed for this project indicated that DH techniques are particularly useful when used together with molecular markers (Appendix).

### 2.2 WHEAT BREEDING METHODS

Two early methods of plant breeding include (1) mass selection, and (2) pureline selection (Baenziger and DePauw, 2009, p. 285). In mass selection, plants that do not appear to belong in the line are removed from the populations, and remaining plants are harvested in bulk. This technique is used to quickly develop more uniform cultivars, but rarely improves yields. As such, mass selection techniques are not often used to create new lines, but are commonly used to purify advanced lines (Baenziger and DePauw, 2009, p. 285). According to Baenziger and DePauw (2009), "Pureline selection attempts to identify and propagate the best individuals in the line, whereas mass selection intends to keep the important aspects of a population" (p. 285).

#### 2.2.1 PEDIGREE SELECTION

Love (1927) defined pedigree selection as a method of breeding in which individual plants are selected from a segregated population of known plants. The pedigree selection method is the oldest wheat breeding method. In this method, individual plants are selected at each segregating generation, and promoted as individual entries. This has been the most widely used method for wheat breeding worldwide, and has some advantages such as the possibility of using previous years' plant based data in selection. However, because of the enormous number of entries to handle, record keeping and nursery preparation becomes very laborious. Pedigree breeding used breeder selection as an active process, and is therefore labor-intensive. However, the method also provides the most genetic information to the breeder (Baenziger and DePauw, 2009, p. 287). Baenziger and DePauw (2009) stated that the pedigree selection method: "...is generally used to create new lines and cultivars that combine the best traits from parent lines" (p. 285).

In the early 1980s, the pedigree selection method was replaced with a combination of pedigree and bulk breeding, named the "modified pedigree/bulk" selection method (Van Ginkel et al. 2002). In the late 1980s, the first preliminary attempts were made to apply what would later be called the "selected bulk" selection method, in which in all generations starting from the F2 plants were bulked, until in the F6 individual spikes were selected and individually promoted to the F7. By the second half of the 1990s, the selected bulk approach began to be quite extensively applied in bread wheat breeding, and it is now the main selection method used at CIMMYT (Van Ginkel et al. 2002; Aquaah 2007).
2.2.2 BULK SELECTION

Bulk selection was developed by the Swedish wheat breeder Nisson-Ehle (Newman 1912), and is similar to the mass selection method described above. In both methods, superior plants are selected. In bulk selection, a sample of selected seed is propagated in the next cycle of inbreeding. In bulk selection, the breeder uses simple selection techniques or natural selection for removing undesirable plants, and the population is harvested in bulk (Baenziger and DePauw, 2009, p. 287). Therefore, bulk selection is less labor-intensive, and thus less expensive, than pedigree selection.

2.2.3 SINGLE-SEED DESCENT

Single-seed descent (SSD) is a method to achieve homozygosity (the condition of possessing two identical forms of a particular gene) with minimal selection (Goulden 1939). The objective of single-seed descent is to reduce the time to achieve near-homozygosity (Baenziger and DePauw, 2009, p. 292). The single-seed descent method is similar to doubled haploid (DH) in this sense. However, Baenziger and DePauw (2009) noted, "Because single-seed descent only samples one seed per individual, the probability of selecting individuals with the maximum number of desirable alleles is greatly reduced (p. 289). Additionally, Baenziger and DePauw (2009) stated that the method should not be used in crosses expected to produce greater genetic variation.

2.2.4 DOUBLED HAPLOID METHOD

This method generates homozygous lines from haploid tissue (Baenziger and DePauw, 2009, p. 291), by doubling chromosomes, resulting in a plant that is completely homozygous and homogeneous (Guzy-Wroblska and Szarekjo, 2003). Laurie and Bennett (1988) described the wheat-by-maize system of doubled haploidy. In this procedure, embryo rescue methods are used to propagate haploid tissue through chromosome elimination in wide crosses when the endosperm does not form. Baenziger and DePauw (2009) concluded that, "Doubled haploidy is an expensive method but requires the least amount of time to develop inbred lines, especially when breeding winter wheat, where the vernalization requirement slows single-seed descent breeding" (p. 291). Importantly, the authors go on to state, "If past history repeats itself, the methods to create doubled haploids will become less expensive and will feature fewer culture-induced variants" (p. 292).

Henry and de Buyser (1990), Picard et al. (1990), and more recently Kasha and Maluszynski (2003), provided excellent overviews of doubled haploid production, and Forster et al. (2007) described recent technological innovations that have brought about a resurgence in haploidy in higher plants. Bonjean and Angus (2001) contributed extensive evidence for doubled haploid use in wheat breeding programs throughout the world, including the United Kingdom, Poland, Denmark, Romania, Brazil, Mexico, New Zealand, Japan, Nepal, and Iran. The authors also provided a thorough technical description of DH methods.
Baenziger and DePauw (2009) emphasized the efficiency of DH wheat breeding is recovery of mutants (p. 292). Most importantly, the authors described enhanced efficiency by using DH and molecular markers in conjunction: "…using molecular markers in selection becomes more efficient because the heterozygous lines have been removed" (p. 292). Baenziger and DePauw (2009) provided a list of successful DH wheat cultivars that have been released and grown commercially (p. 292). Lastly, Forster and Thomas (2005) noted that, "Doubled haploidy has great potential in the production of transgenic crops" (p. 80).

"The most important considerations for [DH] breeders are: investment in good plant production facilities, tissue culture facilities and skilled technical support, and the availability of cheap, efficient, genotype independent protocols" Forster and Thomas, 2005, p. 80.

Forster and Thomas (2005) provided an excellent review of doubled haploids in plant breeding. The authors concluded that, "The rapid attainment of homozygosity at any generation is probably the most valuable feature of doubled haploidy for plant breeding" (p. 72). A second benefit is the development of large numbers of homozygous lines. Forster and Thomas (2005) summarized the use of doubled haploidy: "Despite proven and theoretical benefits of doubled haploidy, deployment in breeding programs must be practical, cost efficient, satisfy breeding objective, and produce marketable cultivars" (p. 72). Two potential downsides of DH were also mentioned: (1) "Although doubled haploidy is useful in fixing rare alleles, overuse may reduce genetic variation in breeding germplasm in which generic diversity may be better preserved in heterozygous lines" (p. 72), and (2) "The application of doubled haploidy, even in the most responsive species, is restricted by genotype dependency and there is a challenge to develop more genotype independent methods… care will be needed to prevent erosion of the breeder's gene pool" (Forster and Thomas, 2005, p. 80).

"Doubled haploidy not only offers an opportunity to speed up traditional breeding methods, but allows greater flexibility in that it can be applied at any generation, allowing rapid response to changing market demands." Forster and Thomas, 2005, p. 74.

Because doubled haploid production methods are labor-intensive, and thus costly, recent research has focused on the attempt to make doubled haploid methods more efficient. Liu et al.
(2002) aimed to develop a more efficient and effective isolated microspore culture system for generating double haploid wheat plants, and Ravi and Chan (2010) reported a method of generating double haploid seeds by manipulating a single centromere protein. The efficiency of the doubled haploid methods can overcome the potential negative characteristics of single-seed descent include time delays and competitive interactions between plants (Forster and Thomas, 2005, p. 74).

### 2.2.5 BACKCROSS METHOD

Briggs (1938) proposed backcrossing, or substituting an undesirable allele with a desirable allele, for a specific trait. The backcross method has been used as a short-term strategy to incorporate dominant genes for the control of harmful pathogens in production cultivars. Baenziger and DePauw (2009) suggested that molecular markers could be used with backcross breeding to promote resistance to wheat cultivars without having to introduce the pathogen into the field (p. 293). Forster and Thomas (2005) opined that backcrossing can be greatly enhanced using DH production in early generations (p. 79).

This chapter has described several methods that wheat breeders use to create and propagate new wheat varieties with desirable characteristics such as higher yields, disease resistance, and end-use qualities. The next chapter will develop and summarize a simple economic model of wheat breeding that captures the important features of wheat variety development from an economic perspective.
CHAPTER THREE. AN ECONOMIC MODEL OF WHEAT BREEDING

3.1 BACKGROUND AND PREVIOUS LITERATURE

The measurement of the economic impact of agricultural research has a large and interesting literature, as summarized by Huffman and Evenson (1993) and Alston, Norton, and Pardey (1995). Blakeslee and Sargent (1982) and Feyerharm et al. (1984) developed an economic framework for the quantification of the economic impact of public research and extension in wheat production. Brennan (1984, 1989a) carefully summarized and measured the impact of the Australian wheat breeding program, providing the foundation for a large literature that has continued this work, using his original research as a template. Brennan's (1989b) work in developing a schematic approach to wheat breeding is particularly important to the model developed here. Byerlee and Traxler (1995) extended Brennan's work by consideration of international wheat breeding improvements since the Green Revolution.

The Kansas wheat breeding program has been evaluated by Barkley (1997) and Nalley, Barkley, and Chumley (2006, 2008). This previous literature demonstrates a large and statistically significant positive impact of the Kansas Agricultural Experiment Station (KAES) wheat breeding program on wheat yields, and thus producer revenues, for producers who purchase and grow varieties developed by the KAES. This research uses the quantitative estimates from Nalley, Barkley, and Chumley (2008) to derive the economic implications of the proposed DH laboratory on the Kansas wheat industry.

"During the "new age" of wheat breeding (1977-2006), wheat breeding alone is found to have increased yields by 6.182 bushels per acre, or an average increase of 0.206 bushels per year." Nalley, Barkley, and Chumley, 2008, p. 913.
3.2 MODEL OF A WHEAT BREEDING PROGRAM

A basic economic model of a wheat breeding program is illustrated in figure 1 (below). The model is considered to be an economic model, since it focuses solely on the dollar value of the costs and benefits of the program, while ignoring agronomic, social, cultural, or any other nonfinancial aspects of the program. In a purely economic analysis, the program follows the typical pattern of an investment: the contribution of money in the current period, with the expectation of future returns.

\[ t_{\text{con}} \] = development time (time to market, TTM), of new wheat variety using conventional breeding assumed to equal 11 years (table 3.1)
One of the most important considerations in this analysis is the "time to market," (TTM) of a wheat variety, developed under two possible methods: (1) conventional, and (2) doubled haploid. Interviews with wheat breeders in both private and public programs were conducted to gain a better estimate of the development times for wheat varieties. The results of these interviews appear in table 3.1, for both conventional and doubled haploid wheat breeding programs.

Table 3.1. Wheat Variety Development Time for Conventional and Doubled Haploid Methods.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Conventional (years)</th>
<th>Doubled Haploid (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario One: Baseline</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>Scenario Two: &quot;Long&quot;</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Scenario Three: &quot;Short&quot;</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

Source: Telephone interviews and e-mail correspondence with wheat development experts, January 25 through February 7, 2011, (Appendix).

The baseline, "Scenario One" is a representative, or "average," length of time for winter wheat variety development, from initial cross of a new variety to public release. To account for variation in wheat breeding programs, we will also consider a "long" wheat varietal development time (Scenario Two, table 3.1), and a "short" development time (Scenario Three, table 3.1).

A stylized wheat breeding program is depicted in figure 1, where the development time of a new wheat variety using conventional methods requires 11 years ($t_{con} = 11$). It is assumed that there are costs for 11 years, followed by a stream of revenues earned by wheat producers after the release of the wheat variety in year 11. The illustration is simplified by assuming constant costs for 11 years, followed by constant revenues for all years after the release of the wheat variety in year 11. This simple schematic diagram captures the main features of the wheat breeding program, although the real world is much more complicated, with several new varieties being developed simultaneously, and fluctuations in cost and revenue streams based on changing economic conditions.

Costs include all of the costs of maintaining the wheat breeding program, including labor, buildings, tools, and equipment, as reported for the period 1977-2006 by Nalley, Barkley, and Chumley (2008). These costs averaged approximately 5 million USD, in constant 2006 dollars. The
economic gains, or revenues, that are attributable to the wheat breeding program are calculated as in equation 3.1, following Nalley, Barkley, and Chumley (2008).

\[
REV_t = A_t \times P_t \times KAES_t \times GEN_t
\]

\[
(mil \ USD) = (mil \ acres) \times (USD/\text{bu}) \times (\%) \times (\text{bu/acre})
\]

Units for each variable in the equation are reported in parentheses below the equation. The variable \( REV_t \) is defined as revenues in year \( t \), and \( A_t \) is acres planted in the geographical area under investigation, Kansas in this case. The variable \( P_t \) is the average market price of wheat in United States Dollars per bushel (USD/bu). The variable \( KAES_t \) is the percent of Kansas wheat acres planted to varieties produced by the KAES, and \( GEN_t \) is the annual rate of genetic gain due to the wheat breeding program, holding constant all other factors such as weather, input use, soil quality, etc. Several features of the revenue calculations are deserve emphasis.

First, the prices are constant, adjusted for inflation, to eliminate the impact of rising general price levels on the dollar value of the program. All prices in the analysis below are presented in constant 2010 USD. Next, the revenues attributable to the KAES estimated using this equation are a conservative estimate, since KAES varieties are planted outside of the state of Kansas. These acres are ignored, not because they are not important, but because of data availability. Wheat varieties developed by KAES are widely grown throughout the Southern Great Plains region. Thus, the dollar values of revenues reported here are underestimates of the actual value of the KAES program. The measure of genetic gain (\( GEN_t \)) is taken from Nalley, Barkley, and Chumley (2008), and is equal to 0.206 bu/acre, representing the annual increase in yields due to the KAES wheat breeding program, holding all other wheat yield determinants constant.

Summary statistics for the variables that appear in equation (1) are reported in table 3.2. The economic variables for the Kansas wheat industry are reported for three time periods; (1) 1977-2006, (2) 2001-2010, and (3) 2006-2010. This analysis uses the average values for the five-year time period of 2006-2010 to reflect the most current data available. These data also reflect smaller numbers for Kansas harvested acres (column one), percent Kansas acres in KAES varieties (column two), and percent Kansas acres in all public varieties (column three). The price of wheat is higher in the selected period, due to the unprecedented high commodity prices that have occurred since 2008 due to biofuels, income growth in low-income nations such as China and India, and poor weather in agricultural regions.

<table>
<thead>
<tr>
<th>Period</th>
<th>Kansas Harvested Acres</th>
<th>% Kansas KAES</th>
<th>% Kansas Public Varieties</th>
<th>Kansas Wheat Price</th>
<th>Annual Genetic Gain</th>
<th>Value of Kansas Wheat</th>
<th>Annual Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977-2006</td>
<td>10,373,333</td>
<td>53.1</td>
<td>69.9</td>
<td>5.93</td>
<td>0.206</td>
<td>2,029</td>
<td>5.41</td>
</tr>
<tr>
<td>2001-2010</td>
<td>8,780,000</td>
<td>50.3</td>
<td>61.4</td>
<td>4.73</td>
<td>0.206</td>
<td>1,610</td>
<td>8.34</td>
</tr>
<tr>
<td>2006-2010</td>
<td>8,680,000</td>
<td>38.4</td>
<td>50.0</td>
<td>5.77</td>
<td>0.206</td>
<td>1,916</td>
<td>8.34</td>
</tr>
</tbody>
</table>

1 USDA/NASS, Kansas Farm Facts.
2 Author calculation, based on USDA/NASS, Wheat Varieties.
3 Dollar values are in real 2010 USD, deflated by the Personal Consumption Expenditure (PCE) of Department of Commerce, Bureau of Economic Analysis (USDC/BEA).

The data reported in table 3.2 are used to estimate the value of the KAES wheat breeding program on an annual basis. This research aims to estimate the economic value of the proposed doubled haploid laboratory to be located in Manhattan, Kansas. To do this, we extend the simple model of a wheat breeding program depicted in figure 1 with a model of the impact to include a DH lab on such a program, as shown in figure 2 (below). There are two impacts of the adoption and use of DH methods on a wheat breeding program. First, the wheat variety development time, or time to market (TTM), can be reduced significantly, (table 3.1). Second, the annual rate of genetic gain (GEN) can be enhanced due to efficiency gains of the DH method, through molecular markers and other techniques that allow DH to enhance the rate of growth in wheat yields. We will consider both potential impacts of DH methods of a wheat breeding program. The first impact of reduced development time is summarized in figure 2. The variable t_con is defined as the development time (time to market, TTM), of new wheat variety using conventional breeding methods, assumed to equal 11 years. The variable t_dh is defined to be the development time (time to market, TTM), of new wheat variety using doubled haploid (DH) breeding methods, assumed to equal 7 years. These two times are the baseline scenario, based on the interviews results (table 3.1).

The reduction in varietal development time (t_con - t_dh = 4) has significant economic impacts on the wheat breeding program, by reducing costs and increasing revenues. Area B1 in figure 2 represents increased revenues from the sale of a new wheat variety four years sooner than conventional methods would allow, and area B2 represents decreased costs of wheat variety development resulting from an earlier release date. Much of the analysis reported here is the measurement and evaluation of areas B1 and B2 using the best estimates available.
**Figure 2. Economic Benefits and Costs of Conventional and Double Haploid Wheat Breeding**

**One Variety, Seven Year Development Time** ($t_{dh} = 7$)

- **B1** = Increased revenues from sale of wheat variety four years sooner than conventional ($t_{con} - t_{dh} = 4$)
- **B2** = Decreased wheat variety development costs from earlier release date ($t_{con} - t_{dh} = 4$)
- **C1** = Initial costs of building doubled haploid laboratory, estimated to be equal to 6 m USD
- **C2** = Annual operating costs of doubled haploid laboratory, estimated to be equal to 1 m USD

$t_{con}$ = development time (time to market, TTM), of new wheat variety using conventional breeding assumed to equal 11 years (table 3.1)

$t_{dh}$ = development time (time to market, TTM), of new wheat variety using doubled haploid breeding assumed to equal 7 years (table 3.1)
The costs of the DH laboratory are disaggregated into two types: (1) building costs \( (\text{BUILDC}_t, \ C_1) \), and (2) annual operating costs \( (\text{ANNUALC}_t, \ C_2) \), as reported in equation 3.2.

\[
(3.2) \quad C_t = \text{BUILDC}_t + \text{ANNUALC}_t
\]

\[
(\text{mil USD}) = (\text{mil USD}) + (\text{mil USD})
\]

In figure 2, area \( C_1 \) represents the initial, one-time, costs of building a doubled haploid laboratory. These costs are estimated to be equal to 6 million USD. The area \( C_2 \) represents the recurring annual operating costs of the proposed doubled haploid laboratory, estimated to be equal to one million USD per year.

The economic model of the adoption and use of a DH laboratory shown in figure 2 emphasizes the large gains in both (1) cost savings in reduced development time, and (2) increased revenues resulting from the earlier release of a new, higher-yielding, wheat variety. The models shown in figures one and two are for a single variety. In a real-world wheat breeding program, these models must be expanded to accommodate continuous advances in wheat varieties, resulting in cumulative gains over time. This more realistic scenario is illustrated in figure 3.

Figure 3 demonstrates the forecasted future agronomic impact of the KAES wheat breeding program, for both the conventional breeding program and the possibility of the program with a DH laboratory, for the next 15 years. The current conventional breeding program provides genetic gains equal to 0.206 bu/year (Nalley, Barkley, and Chumley 2008). If the DH laboratory were to be built in 2011, a new variety could be released seven years later (in 2018), with increased yield potential. One way to think of this discrete jump in future yields is that the new DH variety released in 2018 would have the same genetic potential as varieties released by the conventional wheat breeding program four years later, in 2022, assuming no increase in genetic gain efficiency. However, the illustrated gain is likely to be larger, since it includes the possibility of enhanced efficiency of wheat variety development.

The large discrete change in 2017 reflects the first benefit of the use of Doubled Haploids in wheat breeding. The second benefit is enhanced rate of genetic gain, which is captured by the steeper slope of the yield trend for the DH laboratory case. The graph is drawn assuming that the rate of change in yield potential is 150 percent greater with the use of Doubled Haploids, relative to the baseline scenario of the conventional breeding program.
This model is realistic enough to capture the major economic impacts of the proposed DH laboratory, and simple enough to be estimated with available data. The analysis proceeds in the next chapter with the careful measurement of costs and benefits, and quantification of several summary financial measures.
CHAPTER FOUR. RESEARCH METHODOLOGY

4.1 BACKGROUND

The previous chapter described the development of an economic model of a wheat breeding program, with an extension that allows for the analysis of the economic impacts of the proposed doubled haploid laboratory in Manhattan, Kansas. This chapter describes the empirical application of the economic model, through identification and quantification of the economic costs and benefits of the doubled haploid laboratory. The chapter begins with an overview of financial measures for investment analysis, then describes the parameter values used to quantify the model.

4.2 COST-BENEFIT ANALYSIS

The purpose of this analysis is to estimate the economic impact of the proposed doubled haploid laboratory in monetary terms. The major financial performance indicators that are estimated below include:

✓ Net Present Value (NPV)
✓ Benefit-Cost Ratio (BCR)
✓ Internal Rate of Return (IRR)

The Net Present Value (NPV) is defined as the sum of the present values (PVs) of individual cash flows from a project or business. The NPV summarizes the total discounted economic value of a project. Net Present Value is a preferred method of evaluation because it considers the time value of money (Kay et al. 2012), as shown in equation 4.1, where B represents dollar benefits, C represents costs, i is the "discount rate," assumed to equal ten percent, t is the time period (year), and T is the ending year of the analysis.
(4.1) \[ NPV = \sum_{t=0}^{T} \frac{B}{(1 + i)^t} - \sum_{t=0}^{T} \frac{C}{(1 + i)^t} \]

The **Benefit-Cost Ratio** (BCR) is a financial indicator that attempts to summarize the overall monetary value of a project or proposal (Kay et al. 2012). A BCR is the ratio of the benefits of a project or proposal, expressed in monetary terms, relative to its costs, also expressed in monetary terms. All benefits and costs are expressed in discounted present values, as in equation 4.2. The variables are as defined above for NPV.

(4.2) \[ BCR = \frac{\sum_{t=0}^{T} \frac{B}{(1 + i)^t}}{\sum_{t=0}^{T} \frac{C}{(1 + i)^t}} \]

The **Internal Rate of Return** (IRR) is a measure of the financial rate of return of a project or proposal, where given the (period, cash flow) pairs \((n, C_n)\) where \(n\) is a positive integer, the total number of periods \(N\), and the net present value \(NPV\), the internal rate of return (IRR) is given by \(r\) in:

(4.3) \[ IRR: \quad NPV = \sum_{t=0}^{T} \frac{B}{(1 + r)^t} - \sum_{t=0}^{T} \frac{C}{(1 + r)^t} = 0 \]

The IRR provides information that is not available from either BCR or NPV, since it estimates an actual rate of return comparable to other financial investments (Kays et al. 2012, p. 319).

The financial performance measures described above are used together with the economic model of a proposed doubled haploid laboratory illustrated in figure 2. The overall benefits and costs of the proposed doubled haploid laboratory are captured in the areas C1, C2, B1, and B2 of figure 2, and are estimated using the formulae defined in equations 3.1 and 3.2.

The costs and benefits of the KAES wheat breeding program were described and measured by Nalley, Barkley, and Chumley (2006 and 2008). The estimates presented in this report are for the changes in the cost and revenues streams of the wheat breeding program, assuming that a doubled haploid laboratory were to be built and utilized. The increased costs of building and running the laboratory represent the overall costs. As discussed above, two sources of potential revenue from a doubled haploid laboratory include: (1) faster development time of new wheat varieties (time to market, TTM), and (2) enhanced rate of genetic gain resulting from the use of doubled haploids together with molecular markers, and potential economies to scale that could be achieved with the double haploid breeding method. The measurement of these costs and revenues are described in the next section.
4.3 VARIABLES USED IN THE COST-BENEFIT ANALYSIS

Cost data were acquired through correspondence with Forrest G. Chumley, President and Chief Financial Officer (CEO) of Heartland Plant Innovations, Inc., of Manhattan, Kansas. Building costs (BUILD) are assumed to be six million constant 2010 US dollars, an upper estimate of costs at the time of this study (table 4.2). Annual costs of operating the laboratory (ANNUAL) are assumed to be one million constant 2010 US dollars, also considered to be an upper estimate (table 4.2). Since the cost estimates are likely to be higher than actual costs, the resulting financial measures are conservative estimates, erring on the side of higher costs and lower revenues, to provide conservative estimates of the financial performance measures.

Table 4.2. Assumed Parameter Values of Model Variables.

<table>
<thead>
<tr>
<th>2006-2010 Kansas Wheat Averages</th>
<th>Low</th>
<th>Baseline</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kansas Harvested Acres (million)</td>
<td>8.00</td>
<td>8.68</td>
<td>10.00</td>
</tr>
<tr>
<td>% Kansas acres in KAES varieties</td>
<td>25.00</td>
<td>38.40</td>
<td>50.00</td>
</tr>
<tr>
<td>Wheat Price (2010 USD)</td>
<td>3.27</td>
<td>5.77</td>
<td>7.07</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual Genetic Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
</tr>
<tr>
<td>Doubled Haploid</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time and Discount Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate</td>
</tr>
<tr>
<td>Time Horizon (years)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Doubled Haploid Laboratory Expenditures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building costs, one year (m 2010 USD)</td>
</tr>
<tr>
<td>Annual Operating Costs (m 2010 USD)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variety Development Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
</tr>
<tr>
<td>Doubled Haploid</td>
</tr>
</tbody>
</table>

1 The high value occurred in 2003, the lowest recent value was 8.4 million acres in 2010.
2 The high value is the percentage of Kansas acres in all public varieties (Kansas, Oklahoma, Texas, Nebraska, and Colorado) over the five-year period 2006-2010, the low value is one-half of the high value.
4 The low value represents a constant rate of annual genetic gain for both conventional wheat breeding and doubled haploid (DH) wheat breeding, taken from Nalley, Barkley, and Chumley (2008). The baseline value represents 150% faster annual genetic gain for DH methods, and the high value represents 200% faster annual genetic gain for DH methods.
Following Barkley 1997, and Nalley, Barkley and Chumley (2006, 2008), revenue estimates were made for Kansas only, due to data availability, and to provide a conservative estimate of the economic gains resulting from the proposed doubled haploid laboratory. The revenue estimates were calculated using the formula in equation 3.1, with assumed parameter values presented in table 4.2. The data for harvested wheat acres in Kansas, percent acres planted with KAES varieties, and wheat prices are for the 2006-2010 period. The values used in the analysis are mean (average) values for this most recent five-year period. This method incorporates the most up-to-date data, but eliminates extreme values by averaging, or "data smoothing."

The baseline scenario represents the most accurate estimate of each of the parameters used in the analysis. To gain a deeper understanding of how financial measures change when agronomic and economic conditions change, two additional scenarios were estimated, in which all model parameters are assumed to take on "low" and "high" values, allowing for analysis of how robust our financial estimates are to unexpected changes in parameter values. The values of each of the three scenarios are reported in table 4.2, along with a description of how the "high" and "low" scenario values were selected.

The baseline scenario represents the most accurate estimate of each of the parameters used in the analysis. To gain a deeper understanding of how financial measures change when agronomic and economic conditions change, two additional scenarios were estimated, in which all model parameters are assumed to take on "low" and "high" values, allowing for analysis of how robust our financial estimates are to unexpected changes in parameter values. The values of each of the three scenarios are reported in table 4.2, along with a description of how the "high" and "low" scenario values were selected.

The assumed value for annual genetic gain is taken from Nalley, Barkley, and Chumley (2008). For conventional wheat breeding methods, the value is assumed to remain the same as was estimated for the period 1977-2006 (0.206 bushel per acre per year). As described in the description of the doubled haploid method of wheat breeding above, wheat breeders believe that the annual rate of genetic gain will increase when doubled haploid methods are available and adopted, particularly when used with molecular markers. This enhanced rate of gain in Kansas wheat yields is assumed to be equal to 150 percent in the baseline rate, and 200 percent in the "high" scenario. The "low" scenario uses the conventional wheat breeding rate of genetic gain (0.206 bushels per acre per year, table 4.2). This represents the case where there are no changes in the rate of genetic gain between conventional and doubled haploid wheat breeding methods, an extreme and unlikely case. These rates of change are based on correspondence with wheat breeders (Appendix), and do not reflect any actual measurement. However, the range between zero and 200 percent increase in the rate of annual genetic gain certainly captures the true range that will occur when the doubled laboratory becomes operational.

The financial analysis assumes values of a 50-year time horizon and a discount rate of ten percent. Both parameters are altered in the "high" and "low" scenarios to provide a range of possible financial performance measures, representing the likely economic impact of a doubled haploid laboratory under a wide variety of economic conditions. The varietal development times reported in table 4.2 are those provided by the interviewed wheat breeders, reported in the Appendix and summarized in table 3.1. This chapter has presented an overview of the financial performance measures used to summarize the economic impact of the proposed doubled haploid laboratory, as well as the assumed parameter values of the economic model. In the next chapter, the results of the economic analysis will be presented.
CHAPTER FIVE. RESULTS

5.1 BASELINE RESULTS

The baseline results represent the most likely outcome of the proposed doubled haploid laboratory. The financial results are strong: the Net Present Value (NPV) equals 173 million 2010 USD, and the benefit-cost ratio (BCR) is over 11 (table 5.1). Restated, the overall financial value of the proposed double haploid laboratory is approximately 173 million constant 2010 US dollars, and for every dollar invested in the laboratory, over 11 dollars are returned to the Kansas wheat economy.

Table 5.1. Model Results: Variety Development Time.

<table>
<thead>
<tr>
<th></th>
<th>Scenario</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short</td>
<td>Baseline</td>
<td>Long</td>
</tr>
<tr>
<td>Conventional</td>
<td>8</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Doubled Haploid</td>
<td>6</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Net Present Value (NPV)(^1)</td>
<td>155.091</td>
<td>173.286</td>
<td>125.234</td>
</tr>
<tr>
<td>Benefit Cost Ratio</td>
<td>10.169</td>
<td>11.245</td>
<td>8.404</td>
</tr>
<tr>
<td>Internal Rate of Return</td>
<td>0.341</td>
<td>0.334</td>
<td>0.267</td>
</tr>
</tbody>
</table>

\(^1\) Values are in million 2010 USD, and the assumed discount rate is ten percent.
The baseline internal rate of return (IRR) is equal to 0.334, indicating a high return on the doubled haploid laboratory investment. The wheat breeding industry is highly competitive, with both public and private breeders using similar techniques, methods, and genetic stock. Therefore, these high returns are unlikely to result in large financial gain to wheat breeding programs. Rather, the wheat seed industry and wheat producers are likely to gain from wheat varieties with higher yields. Wheat consumers are also likely to gain from reduced costs of wheat products. Further research will be undertaken to estimate the incidence (who gains, and by how much) of the doubled haploid technology in the Kansas and Great Plains wheat industry.

One major result of applying economic analysis to technological change is that the public wheat seed industry will be able to remain viable and compete with private wheat breeders if they build and adopt the doubled haploid laboratory. In contrast, the public wheat breeding industry is likely to be at a major disadvantage if it does not build and use a DH laboratory. This result is illustrated in figure 3: any wheat breeding program that maintains the status quo of conventional breeding methods would be unable to compete with other breeders who have already adopted doubled haploid methods. As one interviewed private wheat breeder said, "We will get further, faster using DH in wheat variety development."

Wheat breeders who do not adopt doubled haploid (DH) methods will be at a competitive disadvantage relative to breeding programs that are already using DH techniques. Given the significant decrease in wheat variety development times associated with DH methods, any wheat breeding program that does not use DH techniques is likely to be unable to compete with programs that use the new technology.

Financial performance measures were also estimated for "short" and "long" scenarios, and are reported in table 5.1. These results indicate that the overall economic gains of the doubled haploid laboratory are robust to differences in projected wheat development times. Therefore, under the most likely laboratory conditions, the internal rate of return (IRR) varies between 26 and 34 percent, and the benefit-cost ratio (BCR) varies between 8.4 and 11.2. The proposed doubled haploid laboratory would provide significant economic benefits for all of the wheat breeding programs that use it, even if their specific use, breeding methods, and variety development times vary, as is evident in the results presented in table 5.1.
5.2 SENSITIVITY ANALYSIS

This section presents numerous scenarios that capture different parameter values for all of the variables included in the simple model of a wheat breeding program. The term, "sensitivity analysis" refers to how sensitive the model results are to changes in the value of the parameters in the model. The results of the sensitivity analyses presented below confirm the economic viability of the proposed investment in a doubled haploid laboratory, and the robust nature of the financial measures to potential changes in economic, agronomic, and climactic conditions. The results demonstrate that the proposed laboratory is likely to be a financial success under a very wide range of possible situations and events.

5.2.1 KANSAS WHEAT ACRES AND PRICE

Table 5.2 presents the sensitivity analysis for possible fluctuations in economic variables. Specifically, the financial performance indicators remain positive under a wide range of three variables: (1) Kansas wheat acres planted, (2) percentage of Kansas wheat acres planted to KAES varieties, and (3) wheat prices. The internal rate of return varies between 0.266 and 0.367 under a truly diverse set of assumed parameter values. Under virtually any foreseeable circumstances, the doubled haploid laboratory is highly likely to provide economic rates of return much higher than could be obtained in alternative investments.

Table 5.2. Model Sensitivity Results: Kansas Wheat Acres and Price.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Low</th>
<th>Baseline</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kansas Harvested Acres (mil)</strong></td>
<td>8.000</td>
<td>8.680</td>
<td>10.000</td>
</tr>
<tr>
<td>Net Present Value (NPV)¹</td>
<td>158.386</td>
<td>173.286</td>
<td>202.211</td>
</tr>
<tr>
<td>Benefit Cost Ratio</td>
<td>10.364</td>
<td>11.245</td>
<td>12.955</td>
</tr>
<tr>
<td>Internal Rate of Return</td>
<td>0.323</td>
<td>0.334</td>
<td>0.351</td>
</tr>
<tr>
<td><strong>% Kansas acres in KAES varieties</strong></td>
<td>25.0</td>
<td>38.4</td>
<td>50.0</td>
</tr>
<tr>
<td>Net Present Value (NPV)¹</td>
<td>106.914</td>
<td>173.286</td>
<td>230.743</td>
</tr>
<tr>
<td>Benefit Cost Ratio</td>
<td>7.321</td>
<td>11.245</td>
<td>14.641</td>
</tr>
<tr>
<td>Internal Rate of Return</td>
<td>0.282</td>
<td>0.334</td>
<td>0.367</td>
</tr>
<tr>
<td><strong>Wheat Price (2010 USD)</strong></td>
<td>3.27</td>
<td>5.77</td>
<td>7.07</td>
</tr>
<tr>
<td>Net Present Value (NPV)¹</td>
<td>90.959</td>
<td>173.286</td>
<td>216.316</td>
</tr>
<tr>
<td>Benefit Cost Ratio</td>
<td>6.377</td>
<td>11.245</td>
<td>13.789</td>
</tr>
<tr>
<td>Internal Rate of Return</td>
<td>0.266</td>
<td>0.344</td>
<td>0.360</td>
</tr>
</tbody>
</table>

¹ Values are in million 2010 USD, and the assumed discount rate is ten percent.
5.2.2 ANNUAL GENETIC GAIN

One of the important assumptions of the model developed and estimated here is the potential rate of increase of the rate of genetic gain in wheat varieties due to the discovery, introduction, and adoption of doubled haploid methods for the wheat seed industry. Wheat breeders indicated in interviews that the use of double haploid techniques is highly likely to increase the upward trend in yields of newly released wheat varieties. To capture a wide range of possible rate increases in wheat yields, three scenarios were considered: (1) a "low" scenario, where the rate of change in genetic gain remains constant when doubled haploid methods are used, (2) a "baseline" scenario, where the rate change increases by 50 percent, from 0.206 bushels per acre per year to 0.309 bushels per acre per year, and (3) a "high" rate of genetic gain, assumed to be equal to 200 percent, increasing the rate of genetic gain from 0.206 to 0.412 bushels per acre per year (table 5.3).

Table 5.3. Model Sensitivity Results: Annual Genetic Gain.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Low</th>
<th>Baseline</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual Genetic Gain</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>0.206</td>
<td>0.206</td>
<td>0.206</td>
</tr>
<tr>
<td>Doubled Haploid</td>
<td>0.206</td>
<td>0.309</td>
<td>0.412</td>
</tr>
<tr>
<td><strong>Net Present Value (NPV)</strong></td>
<td>59.655</td>
<td>173.286</td>
<td>286.917</td>
</tr>
<tr>
<td><strong>Benefit Cost Ratio</strong></td>
<td>4.527</td>
<td>11.245</td>
<td>17.962</td>
</tr>
<tr>
<td><strong>Internal Rate of Return</strong></td>
<td>0.263</td>
<td>0.334</td>
<td>0.378</td>
</tr>
</tbody>
</table>

1 Values are in million 2010 USD, and the assumed discount rate is ten percent.

The results for the "low" scenario reported in table 5.3 are important to consider. Even if the rate of genetic gain were to remain unchanged, the economic impact of the proposed doubled haploid (DH) laboratory remains positive and large. In this case, the use of DH methods provides large, positive economic returns, including a new present value (NPV) equal to nearly 60 million constant 2010 US dollars, a benefit-cost ratio (BCR) of 4.5, and an internal rate of return (IRR) equal to over 26 percent.

We can conclude that any positive increase in the value of genetic gain forthcoming from the adoption of doubled haploid methods will contribute large economic gains to the Kansas wheat industry. If the rate of genetic gain were to double (the "high" scenario of table 5.3), then the financial indicators are truly impressive, reflecting a large technological shift in the ability of land, labor, and other inputs to produce grain.
5.2.3 TIME AND DISCOUNT PARAMETERS

Table 5.4. Model Sensitivity Results: Time and Discount Parameters.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Discount rate</th>
<th>Net Present Value (NPV)(^1)</th>
<th>Benefit Cost Ratio</th>
<th>Internal Rate of Return</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.075</td>
<td>301.211</td>
<td>16.080</td>
<td>0.334</td>
</tr>
<tr>
<td>Baseline</td>
<td>0.100</td>
<td>173.286</td>
<td>11.245</td>
<td>0.334</td>
</tr>
<tr>
<td>High</td>
<td>0.125</td>
<td>105.470</td>
<td>8.042</td>
<td>0.334</td>
</tr>
<tr>
<td>Time Horizon (years)</td>
<td>25</td>
<td>115.324</td>
<td>8.173</td>
<td>0.332</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>173.286</td>
<td>11.245</td>
<td>0.334</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>183.662</td>
<td>11.804</td>
<td>0.334</td>
</tr>
</tbody>
</table>
\(^1\) Values are in million 2010 USD, and the assumed discount rate is ten percent.

Cost-benefit analysis requires that future dollars be appropriately discounted to account for the "time value of money." Two assumptions that need to be made are: (1) the appropriate "discount rate," or rate that future dollars are valued relative to current dollars, and (2) the length of the "time horizon," or how many future years are to be incorporated into the project. The results demonstrate that the financial outcomes of the estimated model are robust to a wide range of assumed parameter values of the discount rate and the time horizon (table 5.4). The net present value (NPV) varies from a low of 105 million constant US dollars (high scenario) to a high of over 300 million constant 2010 USD (low scenario, table 5.4) under changes in the discount rate, and the benefit-cost ratio varies between 8 (baseline scenario) to 16 (low scenario). However, the large, positive levels of each of the three financial indicators under the range of assumed values provides some evidence that the proposed doubled haploid laboratory is a solid investment opportunity.

5.2.4 DOUBLED HAPLOID LABORATORY EXPENDITURES

Table 5.5 presents additional important and interesting results of the sensitivity analysis: how the costs of the doubled haploid laboratory affect the financial outcomes of the Kansas wheat breeding industry. The simple economic model presented above disaggregated total costs facing the doubled haploid laboratory into two cost categories: (1) one-time building costs, and (2) recurring annual operating costs. Both categories are altered in three scenarios (low, baseline, and high, table 5.5) to quantify the economic impact of cost changes on the wheat breeding program. The results in table 5.5 demonstrate that given a reasonable range of cost assumptions for both building costs and
annual operating costs, the financial outcomes of the proposed doubled haploid laboratory remain solidly favorable relative to other opportunities.

Under a wide range of potential levels of both building and/or annual operating costs, the financial indicators of the doubled haploid laboratory remain robust. Restated, under virtually any reasonable cost situation or eventuality, the doubled haploid laboratory remains financially viable and a solid investment, with returns much higher than alternative investment opportunities.

Table 5.5. Model Sensitivity Results: Doubled Haploid Laboratory Expenditures.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Low</th>
<th>Baseline</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building costs, one year (m 2010 USD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net Present Value (NPV)</td>
<td>174.286</td>
<td>173.286</td>
<td>169.286</td>
</tr>
<tr>
<td>Benefit Cost Ratio</td>
<td>11.951</td>
<td>11.245</td>
<td>9.094</td>
</tr>
<tr>
<td>Internal Rate of Return</td>
<td>0.3465</td>
<td>0.334</td>
<td>0.294</td>
</tr>
</tbody>
</table>

| Annual Operating Costs (m 2010 USD) | 0.5 | 1.0 | 2.0 |
| Net Present Value (NPV) | 178.743 | 173.286 | 162.371 |
| Benefit Cost Ratio | 16.601 | 11.245 | 6.834 |
| Internal Rate of Return | 0.361 | 0.334 | 0.291 |

1 Values are in million 2010 USD, and the assumed discount rate is ten percent.

This chapter has presented the results of the simple economic model of introducing a doubled haploid laboratory into the Kansas wheat breeding industry. The model results demonstrate that the investment in the proposed laboratory would provide solid financial gains, under a very wide range of possible conditions. The next chapter synthesizes and summarizes the results of this study, and presents economic implications for consideration.
CHAPTER SIX. IMPLICATIONS AND CONCLUSIONS

6.1 ECONOMIC IMPACTS OF PROPOSED DH LABORATORY IN KANSAS

This research set out to understand the economic impacts of a proposed doubled haploid laboratory in Manhattan, Kansas. Interviews with wheat breeders were illuminating, and provided quantitative calibration of the major effects of a doubled haploid laboratory. The interviewed wheat breeders identified two major advantages to doubled haploid (DH) technology: (1) greatly accelerated time to market for new wheat varieties, and (2) faster genetic gains in wheat yields. An economic model was built based on previous literature, knowledge of the wheat industry, and information gleaned from the wheat breeder interviews. A baseline scenario was estimated for the most likely set of conditions facing the future of the introduction of a doubled haploid laboratory into the wheat breeding industry of the Great Plains.

The estimated results of the baseline case provided some evidence that both of the advantages of DH methods would provide truly large economic gains to the wheat industry, and to wheat consumers in Kansas, in the United States (US), and throughout the globe. For every dollar spent on a doubled haploid laboratory, over 11 dollars are generated in the wheat market. The economic value of the doubled haploid laboratory is conservatively estimated at over 173 million dollars over the next 50 years, and the rate of return for the doubled haploid laboratory is conservatively estimated at over 33 percent... a much higher return than investing in a bank, or in the stock market. This is a truly significant investment with both a high rate of return and a large gain in the well-being of wheat producers, wheat consumers, and wheat industry participants. Given these large, positive economic gains, we conclude that the sooner the doubled haploid laboratory is built and operational, the sooner wheat producers and consumers will take advantage of the large technological advance that brings with it large economic gains. While it can be challenging to forecast the future, the economic evaluation of the doubled haploid laboratory indicates that the large and socially significant returns are robust to the possibility of future economic changes, including price and quantity movements in wheat markets.
6.2 IMPLICATIONS FOR CONSIDERATION

Economists divide their work into two categories: (1) "positive" economics, and (2) "normative" economics. Positive economics are factual statements and/or analyses, with no value judgments included. In contrast, normative economics include value judgments, or reasoned argument that is not necessarily factual, but based on opinion, or considered reason. All of the work in this report represents positive economics, with the exception of this section. The following five ideas are for contemplation, discussion, and potential action. They represent an economist's views on several features of the proposed doubled haploid laboratory. As such, administrators, executives, and policy makers could carefully consider the following ideas, but not necessarily act on them unless they are considered useful and/or helpful to the firm's goals and objectives.

6.2.1 USE OF NON-SCIENTIFIC NAMES AND LANGUAGE

Perhaps the most important recommendation that a social scientist could make about the proposed DH laboratory is a simple one regarding the name of the lab and the language used to describe the lab. In public relations and marketing, "perception is reality." The goal of any marketing plan should be to generate the appropriate perception about the laboratory and what it does, in non-technical language. The name, "doubled haploid laboratory" is descriptive and useful for those involved in science and/or crop production, but may be a disadvantage when promoting the lab to politicians, potential funding sources, and wheat industry participants.

An alternative name might be, "Pureline Wheat Laboratory," or "Pure Wheat Laboratory," indicating what the lab does. Dropping the technical language should not be seen as an issue, after all, Westar Energy does not call itself a "coal-fired electricity company" or a "nuclear-driven electricity company." Instead, public utilities and private firms often strive to have neutral names to avoid any controversy or negative perceptions. Similarly, language used to describe the DH laboratory and the methodology should be kept simple, direct, and non-technical. An example is the phrase, "embryo transfer." To plant scientists, this term is value-neutral. However, for nonscientists, this term is value-laden, and this type of terminology might be best left for the scientific community.

Public relations and marketing could adopt value-free terminology and language in all letterhead, business cards, names, titles, and all other business items related to the laboratory. Even the term, "biotechnology" is perceived by some to be negative. It is not the job of the laboratory to try to win over public perceptions. Rather, it is crucial to continue to garner public and private financial support. Therefore, all technical and potentially negative language could be usefully altered to provide a more positive face to the new laboratory for producing pure line wheat. One strategy might be to let the Kansas Bioscience Authority and other groups do the work of promoting biotechnology, and concentrate on what the proposed laboratory intends to do: provide pure wheat lines.
6.2.2 INCENTIVES FOR BREEDER USE OF THE DH LABORATORY

The model estimated here assumes that public wheat breeders will use the new laboratory in a manner that will accelerate the time it takes to bring a new wheat variety to market. If public-sector wheat breeders do not use the laboratory, the excellent financial results of the model will not occur. Careful thought and consideration must be given to the incentives, both financial and non-economic, for public sector wheat breeders to use the laboratory. Agronomists in the public sector do not face the same set of market incentives as private wheat breeders. Public budgets for wheat breeding may not have funds for using doubled haploid methods. To the extent that public sector wheat breeders believe that DH methods are expensive, they will need to be convinced, or subsidized, to use the laboratory.

Some of the interviewed wheat breeders indicated that cost is a disadvantage of the doubled haploid laboratory. This attitude could be usefully addressed. It is not only the cost that should be considered, but the relationship between the benefits and the costs. An example is farm equipment: a combine is expensive, but the economic gain makes the large investment a good investment for the wheat producer. This study has shown that the benefits of the doubled haploid laboratory outweigh the costs, so the initial costs of using the laboratory should be given careful consideration by the laboratory administrators. Currently, most private wheat breeders are using doubled haploid techniques, suggesting that the economic return is worth the costs.

If the wheat breeder must pay for the doubled haploids, he or she may not believe that they could use the laboratory for financial reasons. Kansas Wheat and Heartland Plant Innovations must be acutely aware that they must recruit and acquire contracts for a large number of DH seeds quickly. Funds may need to be sought from public or private sources to motivate public sector wheat breeders to use the new facility. The quantitative evidence provided in this report suggests that this type of financial incentive would be in the interests of wheat producers, consumers, and society as a whole. If wheat breeders continue to use conventional plant breeding methods, the potential gains from the laboratory will not be realized.

6.2.3 PUBLIC VS. PRIVATE SECTOR WHEAT BREEDING OUTCOMES

For several decades, public and private wheat breeders have co-existed and competed to produce the highest-yielding, most desirable wheat seeds for Kansas producers and farmers in other wheat growing areas. The participants share the same training, techniques, and seed stock. Given the new economic conditions facing agriculture, it may be difficult for public and private wheat breeders to maintain the same relationships and industry outcomes in the future. Public sector wheat breeders may want to identify specialized aspects of the wheat breeding industry, and partner with private firms. The productive partnership between public and private sector wheat breeders
could be best maintained if the two different programs were to specialize in what each does best. With higher economic rewards and enhanced technology such as doubled haploid techniques, it is likely that the structure of the wheat breeding industry will need to change to capture the true potential of the wheat market.

### 6.2.4 IMPACT OF DH LABORATORY ON WHEAT BREEDING PROGRAM COSTS

Doubled haploid techniques will certainly reduce conventional wheat breeding costs, as can be seen in figure 2. Not only will wheat variety development times decrease, but a great deal of savings are likely to occur in land, labor, greenhouses, and other inputs used to grown wheat during the breeding process outlined in this report. Over time, these cost savings will offset the costs of using the doubled haploid laboratory. As the doubled haploid techniques become more widespread, it is likely that wheat breeding programs will have large and significant cost savings. One primary cause of the cost reduction is the ability of wheat breeders to make selection decisions with smaller populations.

The change out of conventional methods and into biotechnology is likely to result in significant changes in budgets, resources, employees, and personnel relationships between different stakeholders in the wheat variety development process.

> Time and effort spent in better understanding the current employee and input structure of wheat breeding programs, and how it is likely to change under enhanced technology is warranted, and could pay large dividends to industry leaders, administrators, and policy makers who proactively seek to make positive changes to industry formats.

As much of the wheat variety development process is "outsourced" to the doubled haploid laboratory, care must be taken to provide a smooth and rewarding transition to the affected parties and stakeholders.

### 6.2.5 PRICE POINTS FOR DH LABORATORY

One of the most important decisions facing the administrators of the proposed doubled haploid laboratory is how to set the optimal price for use of the lab. The price should be set high enough to cover all costs, but as low as possible to capture the largest number of users. Perhaps the most important characteristic of the price charged per pure wheat line is that it must be dynamic. As in all industries characterized by rapid technological change, the optimal price will change rapidly as economic conditions and use of the new technology grows. The price charged is likely to
decrease as use of the proposed lab grows. The price structure of the doubled haploid laboratory will need to be carefully considered, reviewed, and *constantly* modified.

*A sluggish response in pure wheat lines price decisions to market and industry conditions could result in serious economic consequences.*

It must be emphasized that this section of the report is normative economics, and departs from the factual analysis presented in the rest of the document. It is hoped that these comments and ideas might be helpful when thinking about the future of the proposed doubled haploid laboratory.

The economic analysis presented here suggests that the doubled haploid laboratory is highly likely to be a successful financial investment, with large positive rates of return to Kansas wheat producers and consumers.
REFERENCES


APPENDIX EXPERT INTERVIEW SUMMARY

Ten wheat breeding and wheat development experts were interviewed via telephone and e-mail correspondence during the time period January 25 through February 7, 2011. Each expert was asked the following three questions, and the results are summarized in the scenarios used in this report, and summarized in table 3.1.

1. Advantages of DH technology

2. Estimates of the number of years from initial cross to release for:
   (a) traditional breeding
   (b) DH breeding

3. Advantages in the selection and verification process that would result in either (a) faster releases, or (2) higher yields?