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A Doubled Haploid Laboratory for Kansas Wheat Breeding: An Economic Analysis of Biotechnology Adoption

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Abstract

This research evaluates the use of doubled haploid lines (DHs) to accelerate breeding and gene discovery in wheat breeding. The DH biotechnology greatly accelerates time to market for new wheat varieties and speeds genetic gains in wheat yields. An economic model was built based on previous literature, knowledge of the wheat industry, and information gleaned from wheat breeder interviews. Results show that DH methods would provide large economic gains to Kansas wheat producers and global wheat consumers. The results are robust to a wide variety of scenarios.

Keywords: biotechnology adoption, bost-benefit analysis, doubled haploids, time-to-market, wheat breeding

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Introduction

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, has 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 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 selection techniques typically require six to eight generations to stabilize desired traits, or fix the desired characteristics of higher yield, quality characteristics, disease resistance, or agronomic features into "pure lines" of wheat varieties. Doubled haploids allow wheat breeders to stabilize desired traits in a single year, 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). Doubled haploid production is a form of biotechnology, but is not transgenic biotechnology, and is therefore unlikely to be subject to the resistance among some wheat producers and nations.

Recently, Heartland Plant Innovations (HPI), a public/private partnership, has made plans for the construction of a doubled haploid laboratory in Manhattan, Kansas to be used by public and private wheat breeders. This research analyzed 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 was conducted, with several measures of financial return estimated. This analysis of the impact of doubled haploids on wheat markets was estimated to find the economic benefits and costs to wheat producers and consumers in Kansas, the United States, and the rest of the world. Doubled haploid methods do not replace traditional wheat breeding programs. Rather, they enhance one component of variety development: propagation of a new variety.

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. Although the genetic gains from a wheat breeding program are permanent and cumulative, they are subject to pathogens, diseases, and other challenges that require plant varieties to be constantly improved through maintenance breeding.

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 were 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 used 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 measured and assessed. The details of doubled haploid technology are particularly interesting. Corn pollen is used to pollinate wheat, resulting in new wheat seeds that are genetically pure and stable, each retaining a unique combination of genes carried on their parents' chromosomes. A description of this process is illuminating, since it represents a major technological breakthrough in crop production. This application of biotechnology provides economists and social scientists with a broader knowledge of recent advances in biology and biotechnology and the implications.

Background and Previous Literature

Wheat Breeding Techniques

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. Baenziger and DePauw (2009) and Baenziger et al. (2009) described and evaluated five methods of wheat breeding: (1) pedigree selection, (2) bulk selection, (3) single-seed descent, (4) doubled haploid (DH), and (5) the backcross method. Baenziger and DePauw (2009) 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. Forster and Thomas (2005) concluded, "We do not expect DH production to replace traditional breeding methods; rather it will provide greater efficiency and new options" (p. 80). Specifically, several wheat breeders interviewed for this project indicated that DH techniques are particularly useful when used together with molecular markers (Fritz 2011; Haley 2011; Marshall 2011; Pumphrey 2011; Sears 2011; Shapiro 2011).

The Doubled Haploid 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-Wrobelska 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," and "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" (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 gentotype 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). The authors concluded that, "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" (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).

The use of DH techniques is complementary to traditional, or conventional, wheat breeding programs. The DH production methods could substitute for, or replace, the propagation component of a wheat breeding program, while other major features of a traditional wheat breeding program would remain the same. The economic analysis presented below is for the inclusion of a DH program into the longstanding wheat breeding program; the DH laboratory does not replace the entire program. In particular, a DH program will need to use new germplasm introduced from conventional selection methods to maintain genetic diversity of the wheat industry. The economic benefits of the DH program will remain with the wheat breeders, wheat producers and consumers and the distribution of the benefits between these groups is beyond the scope of the current research.

Over the past 25 years, it has become increasingly common for retail seed prices to include royalties or other license fees payable to the owners of proprietary traits or other genetic technologies that have been incorporated into the seeds' heredity Such payments have become standard for corn and soybeans, although they are just beginning to appear in wheat. Licensed, proprietary traits are just becoming available for wheat. For wheat seeds, royalties are currently being paid in many regions to public sector breeding programs in connection with the use of varieties released from those programs. Generally, these royalties are being charged for use of the base genetics of the variety, not for the proprietary traits. For the program described in this paper, no royalties are due simply for using doubled haploids in breeding a new variety, it is simply a fee-for-service technology. However, using DH lines can greatly accelerate the incorporation of proprietary traits in a new variety, which may result in a variety for which royalties are due and payable. Farmer acceptance of such royalty payments will continue to depend on the value proposition linked to the technology in question. Where farmers have seen a net financial benefit, royalty payments have gladly been made. It remains to be seen how common royalty-bearing proprietary traits will become in wheat.

An Economic Model of Wheat Breeding

The measurement of the economic impact of agricultural research has a large 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) 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 demonstrated 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).

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. Wheat breeder interviews (Fritz 2011; Haley 2011; Marshall 2011; Pumphrey 2011; Sears 2011; Shapiro 2011) provided an average number of years for development for both conventional (11 years) and doubled haploid (7 years) wheat breeding programs (Table 1).

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 1), and a "short" development time (Scenario Three, Table 1). 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 (Figure 1). 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.

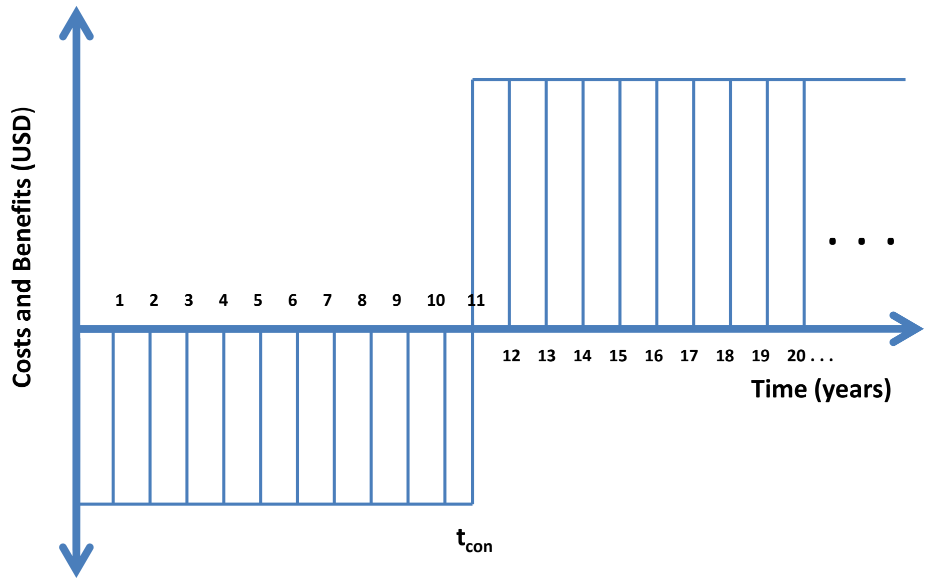

Figure 1. Economic Benefits and Costs of Conventional Wheat Breeding
One Variety, Eleven Year Development Time (t_{con} = 11)

t_{con} = development time (time to market, TTM), of new wheat variety using conventional breeding assumed to equal 11 years (Table 1)

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 (equation 1), following Nalley, Barkley, and Chumley (2008).

$$(1)\ REV_t = A_t * P_t * KAES_t * GEN_t \qquad \text{(mil USD) = (mil acres)*(USD/bu)*(\%)*(bu/acre)}$$

Table 1. Wheat Variety Development Time for Conventional and Doubled Haploid Methods.

Organization	**Breeder**	**Conventional (years)**	**Doubled Haploid (years)**
Pioneer Hi-Bred	Greg Marshall	12	8
Westbred/Monsanto	Joseph Shapiro	12	9
Agripro/Syngenta	Rollin Sears	11	6
Kansas State University	Allan Fritz	10.5	6.5
Colorado State University	Scott Haley	9.5	7
Washington State University	Michael Pumphrey	8	6
Scenario One: Baseline		11	7
Scenario Two: "Long"		12	9
Scenario Three: "Short"		8	6

Source. Telephone interviews and e-mail correspondence with wheat development experts, January 25 through February 7, 2011 (Fritz 2011; Haley 2011; Marshall 2011; Pumphrey 2011; Sears 2011; Shapiro 2011).

Units for each variable in the equation are reported in parentheses following 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). 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 deserve emphasis.

First, implicit in the model are the simplifying assumptions that the rate of genetic gain and the rate of varietal adoption are constant over time. The rate of genetic gain represents a constant average for the period 1977-2005. This rate is likely to change in the future, due to diminishing returns to wheat variety selection, unforeseen developments in wheat breeding, and the variable rate of varietal discovery and release. However, given that the future is uncertain, the approach taken here is to assume that the best forecast of the future rates of genetic gain and varietal adoption are the same as the past, with numerous sensitivity analyses conducted to account for unforeseen changes.

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 were calculated for the economic variables of the Kansas wheat industry (Table 2), 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.

The wheat breeding program data (Table 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 (Figure 1) with a model of the impact to include a DH lab on such a program (Figure 2). 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 1). Second, the annual rate of genetic gain (GEN_t) 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 is reduced development time (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 1).

Table 2. Summary Statistics of Kansas Wheat Breeding Program Variables, 1977–2010.

Period	Kansas Harvested Acres[1] (acres)	% Kansas acres in KAES Varieties[2] (%)	% Kansas acres in Public Varieties[2] (%)	Kansas Wheat Price[1,3] ($/bu)	Annual Genetic Gain[4] (bu/acre)	Value of Kansas Wheat[1,3] (mil USD)	KAES Wheat Breeding Annual Costs[1,3] (mil USD)
1977-2006	10,373,333	53.1	69.9	5.93	0.206	2,029	5.41
2001-2010	8,780,000	50.3	61.4	4.73	0.206	1,610	8.34
2006-2010	8,680,000	38.4	50.0	5.77	0.206	1,916	8.34

[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).
[4] Nalley, Barkley, and Chumley (2008).

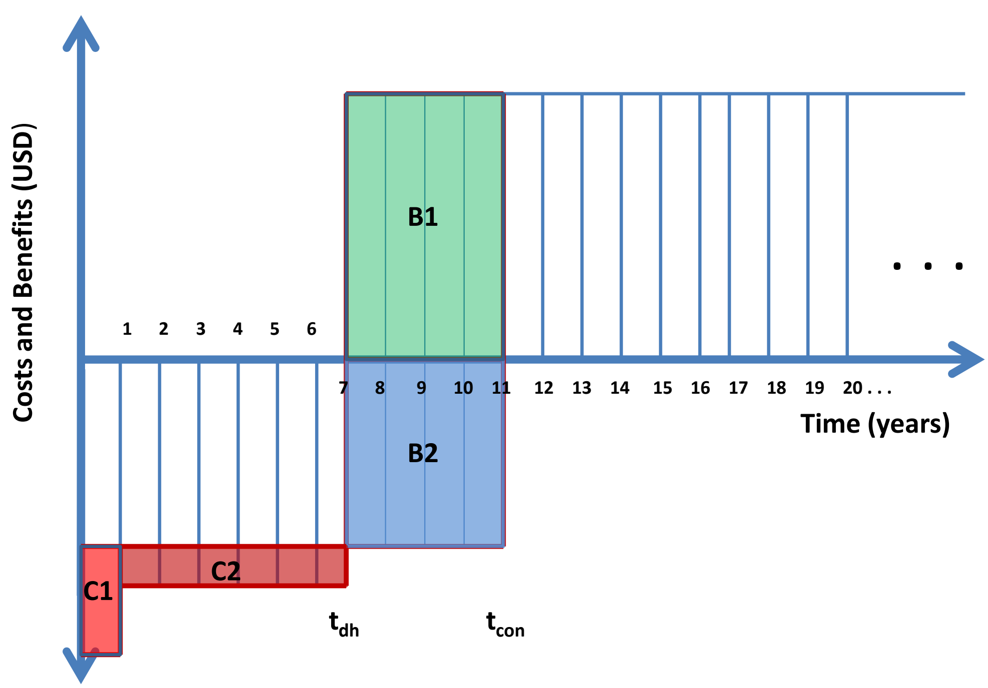

Figure 2. Economic Benefits and Costs of Coventional and Double Haploid Wheat Breeding. One Vareity, Seven Year Development Time (t_{dh} =7)

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 1)
t_{dh} = development time (time to market, TTM), of new wheat variety using doubled haploid breeding assumed to equal 7 years (Table 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 (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. The costs of the DH laboratory are disaggregated into two types: (1) building costs ($BUILDC_t$, C1), and (2) annual operating costs ($ANNUALC_t$, C2, equation 2).

$$(2)\ C_t = BUILDC_t + ANNUALC_t \qquad \text{(mil USD)} = \text{(mil USD)} + \text{(mil USD)}$$

Area C1 (Figure 2) 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 C2 represents the recurring annual operating costs of the proposed doubled haploid laboratory, estimated to be equal to one million USD per year. Recall that the DH laboratory does not replace the traditional wheat breeding program, but enhances the variety propagation component of the program. The economic model of the adoption and use of a DH laboratory (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 developed above 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 incorporated into the model (Figure 3).

This more realistic model (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). This rate isolates the impact of genetic advances on yield, holding all other factors constant in a multiple regression framework. 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 rate of change is based on wheat breeder interviews (Fritz 2011; Haley 2011; Marshall 2011; Pumphrey 2011; Sears 2011; Shapiro 2011), further discussed below. The analysis proceeds in the next section with the careful measurement of costs and benefits, and quantification of several summary financial measures.

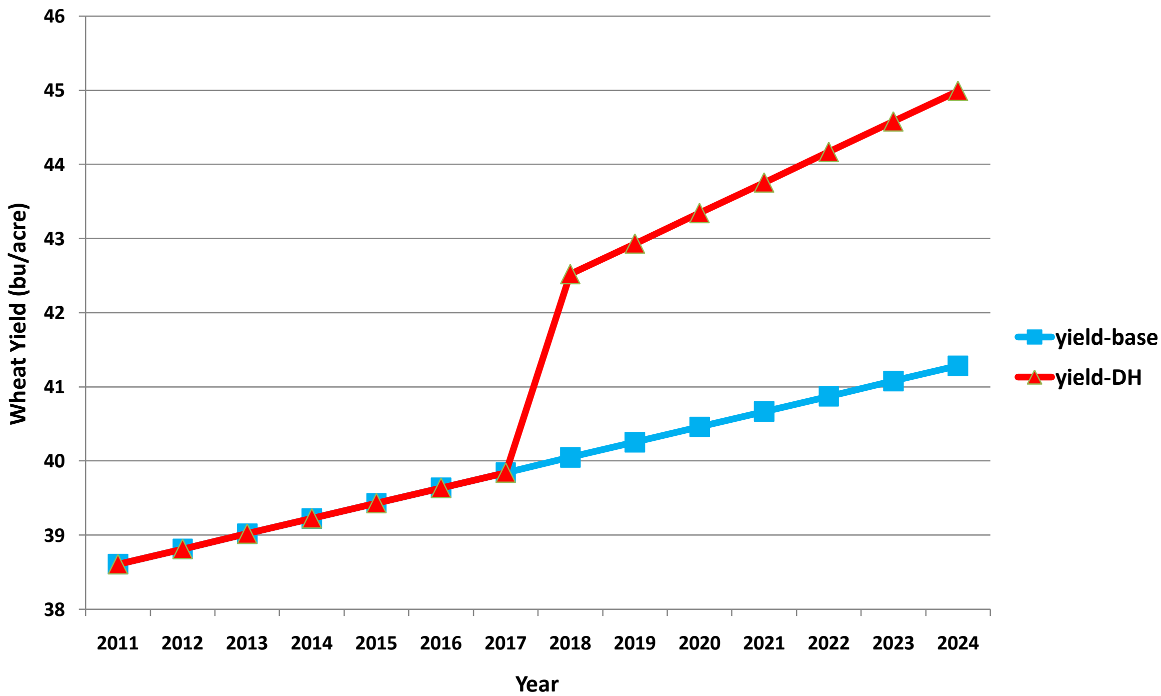

Figure 3. Comparison of Conventional and Double Haploid Wheat Variety Development: Agronomic Benefits. Seven Year Development Time, Increase in Genetic Gain

Research Methodology: 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: (1) Net Present Value (NPV), (2) Benefit-Cost Ratio (BCR), and (3) 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 (equation 3). Net Present Value is a preferred method of evaluation because it considers the time value of money (Kay et al. 2012), 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.

(3) $NPV = \Sigma B/(1+i)^t - \Sigma C/(1+i)^t, \quad t = 0, \dots, T$

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 (equation 4). The variables are as defined above for NPV.

(4) $BCR = [\Sigma B/(1+i)^t] / [\Sigma C/(1+i)^t], \quad t = 0, \dots, T$

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, Cn) 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:

(5) IRR: $NPV = \Sigma B/(1+r)^t - \Sigma C/(1+r)^t = 0, \quad t = 0, \dots, T$

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 (Kay et al. 2012, p. 319).

The financial performance measures described above are used together with the economic model of a proposed doubled haploid laboratory (Figure 2) to estimate the economic impacts of the proposed laboratory. The overall benefits and costs of the proposed doubled haploid laboratory are captured in the areas C1, C2, B1, and B2 (Figure 2), and are estimated using the formulae for benefits (equation 1) and costs (equation 2).

Variables Used in the Cost-Benefit Analysis

Building costs ($BUILDC_t$) are assumed to be six million constant 2010 US dollars, an upper estimate of costs at the time of this study (Table 3). Annual costs of operating the laboratory ($ANNUALC_t$) are assumed to be one million constant 2010 US dollars, also considered to be an upper estimate (Table 3). 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.

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 (equation 1), with assumed parameter values (Table 3). The data for harvested wheat acres in Kansas, percent acres planted with KAES varieties, and wheat prices are for the 2006-2010 period. The trend is toward lower use of public wheat varieties, including KAES varieties (Table 2). Therefore, the “baseline” and “low” scenarios for percent Kansas acres in KAES varieties is likely to be appropriate in the future. 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."

Table 3. Assumed Parameter Values of Model Variables.

	Assumed Parameter Values		
	Low	**Baseline**	**High**
2006-2010 Kansas Wheat Averages			
Kansas Harvested Acres (million)[1]	8.00	8.68	10.00
% Kansas acres in KAES varieties[2]	25.00	38.40	50.00
Wheat Price (2010 USD)[3]	3.27	5.77	7.07
Annual Genetic Gain [4]			
Conventional	0.206	0.206	0.206
Doubled Haploid	0.206	0.309	0.412
Time and Discount Parameters			
Discount rate	0.075	0.100	0.125
Time Horizon (years)	25	50	100
Doubled Haploid Laboratory Expenditures			
Building costs, one year (m 2010 USD)	5	6	10
Annual Operating Costs (m 2010 USD)	0.5	1.0	2.0
Variety Development Time			
Conventional	8	11	12
Doubled Haploid	6	7	9

[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.
[3] Marketing year average price; low value from 2001, high value from 2008.
[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.

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 were calculated (Table 3), given the selected "high" and "low" scenario values (Table 3).

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 3). 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. However, if the rate of genetic advance slows due to diminishing returns in wheat variety selection, the "low" scenario could reflect that possibility. These rates of change are based on correspondence with wheat breeders (Fritz 2011; Haley 2011; Marshall 2011; Pumphrey 2011; Sears 2011; Shapiro 2011), 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. Note that all genetic contributions in wheat breeding are permanent and cumulative. Thus, even if the DH technology is replaced or becomes obsolete in the future time period under considerations, the benefits will continue to accumulate. The varietal development times (Table 3) were provided by the interviewed wheat breeders (Fritz 2011; Haley 2011; Marshall 2011; Pumphrey 2011; Sears 2011; Shapiro 2011).

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 4). 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 4. Model Results: Variety Development Time.

	Scenario		
	Short	**Baseline**	**Long**
Conventional	8	11	12
Doubled Haploid	6	7	9
Net Present Value (NPV)[1]	155.091	173.286	125.234
Benefit Cost Ratio	10.169	11.245	8.404
Internal Rate of Return	0.341	0.334	0.267

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

The baseline internal rate of return (IRR) equals 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. 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 (Figure 3). Since the per-unit costs of using the DH lab are not significant, the use of DH will allow public and private wheat breeders to use the technology equally.

One interviewed private wheat breeder said, "We will get further, faster using DH in wheat variety development" (Shapiro). 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 (Table 4). 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 (Table 4).

Sensitivity Analysis

The results demonstrate that the proposed laboratory is likely to be a financial success under a very wide range of possible situations and events.

Kansas Wheat Acres and Price

Sensitivity analyses were conducted for possible fluctuations in economic variables. Results indicate that 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 (Table 5). The internal rate of return varies between 0.266 and 0.367 under a wide variety 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.

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 6).

Table 5. Model Sensitivity Results: Kansas Wheat Acres and Price.

	Scenario		
	Low	**Baseline**	**High**
Kansas Harvested Acres (mil)	8.000	8.680	10.000
Net Present Value (NPV)[1]	158.386	173.286	202.211
Benefit Cost Ratio	10.364	11.245	12.955
Internal Rate of Return	0.323	0.334	0.351
% Kansas acres in KAES varieties	25.00	38.40	50.00
Net Present Value (NPV)[1]	106.914	173.286	230.743
Benefit Cost Ratio	7.321	11.245	14.641
Internal Rate of Return	0.282	0.334	0.367
Wheat Price (2010 USD)	3.27	5.77	7.07
Net Present Value (NPV)[1]	90.959	173.286	216.316
Benefit Cost Ratio	6.377	11.245	13.789
Internal Rate of Return	0.266	0.344	0.360

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

Table 6. Model Sensitivity Results: Annual Genetic Gain.

	Scenario		
	Low	**Baseline**	**High**
Annual Genetic Gain			
Conventional	0.206	0.206	0.206
Doubled Haploid	0.206	0.309	0.412
Net Present Value (NPV)[1]	59.655	173.286	286.917
Benefit Cost Ratio	4.527	11.245	17.962
Internal Rate of Return	0.263	0.334	0.378

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

The results for the "low" scenario (Table 6) 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 ("high" scenario, Table 6), then the financial indicators are truly impressive, reflecting a large technological shift in the ability of land, labor, and other inputs to produce grain.

Time and Discount Parameters

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 7). 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 7) 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.

Table 7. Model Sensitivity Results: Time and Discount Parameters.

	Scenario		
	Low	**Baseline**	**High**
Discount rate	0.075	0.100	0.125
Net Present Value (NPV)[1]	301.211	173.286	105.470
Benefit Cost Ratio	16.080	11.245	8.042
Internal Rate of Return	0.334	0.334	0.334
Time Horizon (years)	25	50	100
Net Present Value (NPV)[1]	115.324	173.286	183.662
Benefit Cost Ratio	8.173	11.245	11.804
Internal Rate of Return	0.332	0.334	0.334

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

Doubled Haploid Laboratory Expenditure

Additional important and interesting results of the sensitivity analysis include how the costs of the doubled haploid laboratory affect the financial outcomes of the Kansas wheat breeding industry (Table 8). 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 8) to quantify the economic impact of cost changes on the wheat breeding program. The results 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 (Table 8).

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 8. Model Sensitivity Results: Doubled Haploid Laboratory Expenditures.

	Scenario		
	Low	**Baseline**	**High**
Building costs, one year (m 2010 USD)	5	6	10
Net Present Value (NPV)[1]	174.286	173.286	169.286
Benefit Cost Ratio	11.951	11.245	9.094
Internal Rate of Return	0.3465	0.334	0.294
Annual Operating Costs (m 2010 USD)	0.5	1.0	2.0
Net Present Value (NPV)[1]	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.

Implications and Conclusions

This research set out to measure and analyze the economic impacts of a proposed doubled haploid laboratory in Manhattan, Kansas. Interviews with wheat breeders 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. This is a 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 a wide range of possible future economic changes, including price and quantity movements in wheat markets. 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

Alston, J.M., G.W. Norton, and P.G. Pardey. 1995. *Science under Scarcity: Principles and Practice* for Agricultural Research and Evaluation and Priority Setting. Ithaca, NY: Cornell University Press.

Acquaah, G. 2007. *Principles of Plant Breeding and Genetics*. Blackwell Publishing Ltd., Malden, MA.

Baenziger, P.S. and R.M. DePauw. 2009. Wheat Breeding: Procedures and Strategies. In *Wheat: Science and Trade*. Ed. B.F. Carver, 13: 275-308, Ames, Iowa: Wiley-Blackwell.

Baenziger, P.S., R. Graybosch, D. Van Sanford, and W. Berzonsky. 2009. Winter and Specialty Wheat. *Cereals* 251-265.

Barkley, A. 1997. Kansas Wheat Breeding: An Economic Analysis. *Report of Progress* 793. Manhattan, KS: Kansas State University Agricultural Experiment Station and Cooperative Extension Service, October.

Blakeslee, L., and R. Sargent. 1982. *Economic Impacts of Public Research and Extension Related to Wheat Production in Washington*. Research Bulletin XB 0929. Pullman, WA: Agricultural Research Center, Washington State University.

Bonjean, A.P., and W.J. Angus (eds.). 2001. *The World Wheat Book: A History of Wheat Breeding*. Paris, France: Lavoisier Publishing.

Brennan, J.P. 1984. Measuring the Contribution of New Varieties to Increasing Wheat Yields.'' *Review of Marketing and Agricultural Economics* 52(12):175–95.

Brennan, J.P. 1989a. An Analysis of the Economic Potential of Some Innovations in a Wheat Breeding Programme. *Australian Journal of Agricultural Economics* 33(April):48–55.

Brennan, J.P. 1989b. An Analytical Model of a Wheat Breeding Program. *Agricultural Systems* 31 (April):349–66.

Byerlee, D., and G. Traxler. 1995. National and International Wheat Improvement Research in the Post-Green Revolution Period: Evolution and Impacts. *American Journal of Agricultural Economics* 77(May):268–78.

Feyerherm, A.M., G.M. Paulsen, and J.L. Sebaugh. 1984. Contribution of Genetic Improvement to Recent Wheat Yield Increases in the USA. *Agronomy Journal* 76(November):985–90.

Forster, B.P., E. Heberle-Bors, K.J. Kasha, and A. Touraev. 2007. The Resurgence of Haploids In Higher Plants. *Trends in Plant Science* 12(8): 368-375.

Forster, B.P., and W.T.B. Thomas. 2005. Doubled Haploids in Genetics and Plant Breeding. *Plant Breeding Reviews* 25:57-88.

Fritz, Allan. 2011. Kansas State University Wheat Breeder. Manhattan, Kansas 66506. Telephone interview. January 26.

Fuglie, K.O., and T.S. Walker. 2001. Economic Incentives and Resource Allocation in U.S. Public and Private Plant Breeding. *Journal of Agricultural and Applied Economics* 33:459–73.

Guzy-Wrobelska, J., and I. Szarekjo. 2003. Molecular and Agronomic Evaluation of Wheat Doubled Hploid Lines Obtained through Maize Pollination and Anther Culture Methods. *Plant Breeding* 122:305-313.

Haley, Scott. 2011. Colorado State University Wheat Breeder. Ft. Collins, Colorado. Telephone interview. January 26.

Henry, Y., and J. de Buyser. 1990. heat Anther Culture: Agronomic Performance of Doubled Haploid Lines and the Release of a New Variety 'Florin'." In: *Biotechnology in Agriculture and Forestry*, Vol. 13 *Wheat* (ed. Y.P.S. Bajaj). Springer-Verlag Berlin, Heidelberg.

Huffman, W.E., and R.E. Evenson. 1993. *Science for Agriculture: A Long-Term Perspective*. Ames, IA: Iowa State University Press.

Kansas Agricultural Statistics. 2010. *Crops* 10(7).

Kasha, K.J., and M. Maluszynski. 2003. "Production of doubled haploids in crop plants (Introduction)." In: Maluszynski M, Kasha KJ, Forster BP, Szarejko I (eds.) *Doubled haploid production in crop plants, a manual*. 1–4. Kluwer Academic, Dordrecht Boston London.

Kay, R.D., W.M. Edwards, and P.A. Duffy. 2012. *Farm Management*. Seventh Edition. New York, New York: McGraw-Hill.

Laurie, D.A., and M.D. Bennett. 1988. "The Production of Haploid Wheat Plants from WheatxMaize Crosses." *Theoretical and Applied Genetics* 76:393-397.

Liu, W., M.Y. Zheng, E.A. Polle, and C.F. Konzak. 2002. Highly Efficient Doubled-Haploid Production in Wheat (*Triticum aestivum* L.) via Induced Microspore Emryogenesis." *Crop Science* 42:686-692.

Marshall, Greg. 2011. Pioneer Hi-Bred Wheat Breeder. Windfall, Indiana. Telephone interview. January 25.

Nalley, L.L., A. Barkley, and F.G. Chumley. 2006. *The Agronomic and Economic Impact of the Kansas Agricultural Experiment Station. Wheat Breeding Program, 1977–2005*. Manhattan, KS: Kansas State University Agricultural Experiment Station and Cooperative Extension Service, Report of Progress 948, June.

Nalley, L.L., A. Barkley, and F. Chumley. 2008. The Impact of the Kansas Wheat Breeding Program on Wheat Yields, 1911–2006. *Journal of Agricultural and Applied Economics*, 40 (3):913–925.

Picard, E., et al. 1990. "Wheat (*Triticum aestium*): In Vitro Production and Utilization of Doubled Haploids." In: *Biotechnology in Agriculture and Forestry*, Vol. 12 *Haploids in Crop Improvement I* (ed. Y.P.S. Bajaj). Springer-Verlag Berlin, Heidelberg.

Pumphrey, Michael. 2011. Washington State University Wheat Breeder. Pullman, Washington. E-mail correspondence. January 26.

Ravi, M., and S.W.L. Chan. 2010. Haploid Plants Produced by Centromere-Mediated Genome Elimination. *Nature* 464(25):615-619.

Sears, Rollin. January 26, 2011. Agripro/Syngenta Wheat Breeder. Junction City, Kansas. E-mail correspondence.

Shapiro, Joseph. 2011. Westbred/Monsanto Wheat Breeder. St. Louis, Missouri. Telephone interview. February 7.

United States Department of Agriculture. National Agricultural Statistics Service (USDA/NASS). 2010. *Kansas Farm Facts 2010*. Internet site: http://www.nass.usda.gov/Statistics_by_State/ Kansas/Publications/Annual_Statistical_Bulletin/index.asp (accessed February 2011).

United States Department of Agriculture. National Agricultural Statistics Service (USDA/NASS). Various years. *Wheat Varieties*. Internet site: http://www.nass.usda.gov/Statistics_by_State /Kansas/Publications/Crops/Whtvar/whtvar11.pdf (accessed February 2011).

United States Department of Agriculture. Economic Research Service (USDA/ERS). 2011. *Wheat Yearbook* Tables. Internet site: http://www.ers.usda.gov/data/wheat/ WheatYearbook.aspx (accessed February 2011).

United States Department of Commerce. Bureau of Economic Analysis (USDC/BEA). 2011. U.S. National Economic Accounts, Personal Consumption Expenditures (PCE). *National Income and Product Accounts Tables*. Internet site: http://www.bea.gov/national (accessed February 2011).

Van Ginkel, M., R.M. Trethowan, K. Ammar, J. Wang, and M. Lillemo. 2002. *Guide to Bread Wheat Breeding at CIMMYT*. Wheat Program Special Report No. 5. (Revised Edition.) Mexico, D.F.: CIMMYT.

