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GENETIC EDITING (GE) VERSUS GENETIC MODIFICATION (GM) IN THE RESEARCH AND DEVELOPMENT OF NEW CROP VARIETIES: AN ECONOMIC COMPARISON

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ABSTRACT

Genetic editing (GE) offers an additional tool to traditional crop breeding and genetic modification (GM) for developing new traits in agricultural crops. Surveys of leading crop technology companies and a review of the literature indicate that GE may offer considerable economies of scale when compared to GM crop development. These economies are generally attributed to lower R&D costs, higher probability of R&D success (particularly in the initial discovery phase), and the fact that GE crops do not require an extra regulatory approval step (at least in most countries outside the EU) that adds considerable cost and uncertainty to the GM development process.

This study examines the economics of GE versus GM crop development from the perspective of the minimum required market size (in terms of potential crop area) of a potential crop in order for the technology firm to expect to break even in terms of the real option value (ROV) of the project. The valuation model is unique in that it combines a decision tree with a binomial lattice in the valuation of an abandonment real option on the new crop technology. The decision tree is used to model the R&D process (which is non-market driven) while the binomial lattice is used to value the market-driven commercialization of the candidate crop variety. A survey of industry experts provided a range of values with regards to the time and cost of each R&D phase for both GE and GM crop development, so stochastic simulation was incorporated into the ROV model.

A primary result from the empirical model is that across a wide range of trait values, the required cropping area for breaking even on a GE crop variety was consistently 96.3% less than the area required for a GM crop with the identical trait value and commercialization profile. Sensitivity analysis indicated that the GM (and GE to a lesser extent) required area was highly sensitive to the probability of success in the discovery phase. Somewhat surprising, the results for GM and GE were not sensitive to the abandonment option parameters – an indication that this type of real option adds little value to projects primarily due to the low volatility of returns during the commercialization phase.

Genetic Editing (GE) Versus Genetic Modification (GM) in the Research and Development of New Crop Varieties: An Economic Comparison

David W. Bullock, William W. Wilson, and Joseph Neadeau[1]

INTRODUCTION

In the past decade two important phenomena have occurred which are impacting the technological development of crops. One of these is commonly referred to as the 9 billion people problem (The Economist 2011) which suggests that world food production will have to double by 2050. This is due to increased demand for quantity and differentiation. It is also driven partly by changes in worldwide demographics, and by the combined effects of increased urbanization, income, and women in the work force. All of these factors suggest an increase in demand and quality of foods which is exacerbated by reduced plantings in many regions of the world. The second phenomena relates to the impact of the increase in the number of consumer segments for food which is becoming apparent as markets mature. An impact of this is the presence of growing demands for differentiation in foods. Indeed, consumers are now more inclined to demand ingredients and products with specific traits (e.g., non-GM, organic, pure labels, etc.) that present challenges to the food industry.

Concurrent with these changes is an important evolution that is underway in crop technology and breeding. Prior to the mid-1990s, conventional and accelerated breeding practices were the dominant technologies in crop development. This was followed in the mid-1990's by advances in genetic modification (GM) which became dominant for large-area crops and widely desired (commonly referred to as *bonzai* in the industry vernacular) producer traits. More recently, genetic editing (GE) tools, such as CRISPR, have come to the forefront of crop development. This technology is particularly attractive for crops and/or traits that may have a smaller potential area (or marketplace) when compared to GM. In addition, numerous other tools have been advanced which have helped the breeding industries such as double haploids, hybrid marker-assisted-selection, seed chipping, whole genome sequencing, and demonic selection. These are in addition to the recent advent of 'speed-breeding' (Hickey et al. 2019; Sheikh 2019) using controlled greenhouses to accelerate plant growth for more tolerant crops. All of these have provided more tools to the development of crops with the primary effect of accelerating and differentiating among varieties available to the market.

These technologies are characterized as having different technical processes, costs, and time required for development. GM is a technology that typically has five primary phases including trait discovery, proof of concept, early development, advanced development, and regulatory approval – which can be very costly from a financial and time perspective. There are few

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estimates of the cost of developing a GM trait. One is by the Phillips McDougall (2011) consulting firm who estimated that the discovery, development, and regulatory approval of a new GM crop trait requires, on average, approximately US$136 million and 11.7 years to develop. A case study on Monsanto reported that a new GM crop has a 5% probability of success in the discovery stage, which then increases to 90% by the regulatory stage (Bell and Shelman 2006). Wynn et al. (2017) derived actual investment costs incurred in developing a GM trait in Australia which are lower than other publicly disseminated, global market-focused estimates for technology development and commercialization. To our knowledge, estimates of cost and time for development of GE crops are not publicly available. Certainly, the GE companies have estimates, but, there is little or no public information on these data. However, Calyxt (2019) indicated the time for trait development for GE (3-6 years) is substantially lower than for GM and the costs are substantially less. These prospective reduced costs of GE have important implications for product development and competition. This phenomenon is illustrated in this study, and has recently been suggested in a report by Stephens Market Research (2019). Specifically, they alleged that GE technology allows firms to focus on output traits (as opposed to input traits) that may have a higher value to the consumer (as compared to the producer).

Differences in cost and time for development are important for trait developers and competition. Irrespective of the breeding technology being used, trait developers confront two important features which should be elements of analysis for trait development strategy. One of these is risk which is measured as the probability of successfully completing a phase in the R&D process. Specifically, each technology has a series of phases for development and there is risk related to successfully completing each of these R&D phases. These are well known for GM and are described here for GE. Second, at the successful completion of each phase, technology developers have the option of continuing to the next phase (incurring additional R&D cost and time) or to sell (or license) the technology to a third-party for a particular (salvage) value. Based on the value of this real option (known as an "abandonment option" or "option to abandon" in the popular vernacular), the technology may or may not continue to be developed by the technology firm or "exercised" by the sale or licensing to the third-party. For these reasons, it is well known that the use of the traditional *discounted cash flow* (DCF) analysis typically understates the return to technology development. The use of real option valuation (ROV) as a augmentive procedure (to DCF analysis) is generally preferred when attaching value to projects where some decisions can be deferred to a later date (Kodukula and Papudesu 2006).

The purpose of this study was to develop a real option valuation (ROV) model that can be used to analyze the costs and risks of developing traits using either GE or GM technology. For each technology, the phases of development are discerned, and a survey was conducted of firms to elicit estimates of development costs, risk, and time required at each phase of development. The ROV model was applied to the valuation of a same generic trait developed alternatively using GM and GE technologies with comparisons made regarding the required minimum scale (in potential crop area) necessary for the technology firm to expect to break even in ROV value. The results showed a profound difference in the costs, risk, and minimum scale necessary for developing traits using these technologies. These results have important implications for the crop development industry.

The focus of this study is on wheat, a crop of interest to each of GM and GE development, though the general results are similarly applicable to other crops. The structure of this study is as follows. In the next section, previous related studies and background information are described and discussed. This is followed by a conceptual discussion of the empirical ROV Monte Carlo simulation model that is used in this study. A discussion of the data and specific assumptions employed in this study follows. This is followed by the base case results and sensitivities derived from the ROV model simulations. The final section contains a summary of the results with implications for the industry along with suggestions for future research in this area.

BACKGROUND AND PREVIOUS STUDIES

This section provides a brief overview of the evolution of genetic modification (GM) and genetic editing (GE) technologies with a particular focus on the current initiatives for commercialization in the industry. Comparisons between the two technologies are made where appropriate. This is followed by a section containing an overview of the use of real options as an analytical tool with a particular focus upon applications in technology development and the life sciences.

Evolution of GM and GE Technology and Commercialization

Genetic modification (GM) and genetic editing (GE) are two very important technologies currently employed in crop varietal development. In a very simple way, these technologies can be compared as technologies that "knock-in" versus "knock-out" genetic material, respectively, for GM and GE. GM plants are created by inserting another organism's DNA (transgene insertion) into the original plant's DNA. The Flavr Savr tomato, developed in 1994, is widely considered to be the first GM crop that was approved for consumption. By 2015, it was estimated that GM crops were grown on 445 million acres or 10% of cultivable land.

Two major DNA transfer methods are utilized in the process of creating a new GM plant. In one method, metal particles are covered with the relevant DNA from some outside organism. The metal particles are then shot at many of the plant's original cells, with the hope that the plant will successfully incorporate the DNA. The second method is the agrobacterium tumefaciens method (ATM). Simply, relevant DNA is added to a bacterium with the hope that the bacterium can transfer the DNA to the plant's genetic code. GM involves a substantial trial and error process that results in significant costs and elapsed time during the R&D phases which is a result of the overall lack of precision in the aforementioned GM transfer methods.

Regardless of its high cost and long developmental timeline, there are substantial benefits a new GM crop variety can provide. GM technology has been very successful in some larger-area crops that have great potential adoption including corn, soybean, canola, and cotton. Most early GM development focused upon producer desired traits with a high rate of adoption including those that reduce production costs through lower application of chemical herbicides (such as Roundup Ready soybeans) and insecticides (such as Bt corn).

GE varieties are created by cutting out a part of a plant's DNA or editing a part of the plant's DNA (transgene or non-transgene insertion)[2]. Compared to GM, GE is a relatively new technology and advances in the technology are being still being made. Like GM, GE technologies have multiple pathways that can be used to "edit" a plants genome.

There are nine genome editors (as of 2017) with Mega nucleases, Zinc Finger, TALEN, and CRISPR being the most popular. Unlike GM, which largely depends on trial and error, GE technologies have greater precision. For this reason, it may take five or more cycles to achieve the intended result using GM in contrast to GE. Because of the precision of GE, it takes only one or two cycles to achieve the intended result. Added precision is not the only positive result of GE. Because GE can change a plant's genome without the use of another organism's DNA, GE plants may avoid regulations that apply to GM plants. Tools such as CRISPR and TALEN are relatively new, so new that few companies have yet to commercialize GE crops.

A recent study (Martin-Laffon, Kuntz and Ricroch 2019) analyzed the worldwide adoption of CRISPR. The results illustrated the wide and rapid adoption of CRISPR patents. Results indicate that the United States had the most patents but was followed closely by China, and more distantly by the European Union, Korea, and Japan, among others. Much of the growth has been since 2011-2012 with the United States leading in adoption. However, China's growth in patents accelerated after 2013, and by 2016, China had an adoption rate comparable to the United States. The results also indicated that many of the patent holders were public and educational institutions. Among private firms, DuPont-Pioneer had 20 patents, followed by Monsanto, Bayer and Syngenta. CRISPR has applications across numerous industries including medical, industrial, plant-based, and animal-based developments. The dominant plant-based category was for plant breeding with rice being the dominant crop followed by maize, wheat, tomatoes, potatoes, tobacco, and cotton, along with other smaller crops. The patents primarily covered traits related to male sterility, herbicide tolerance, virus resistant fungi, bacteria resistance, and pest resistance along with lesser developed traits.

Development of technologies is conventionally interpreted to encompass all phases of development. Importantly, estimates are made of duration, cost, and probability of success for each phase. These were depicted early on by Monsanto (Bell and Shelman 2006) for GM crop development. Those phases for GM include what is typically referred as: Discovery (D), Proof of Concept (P1), Early Development (P2), Advanced Development (P3), and Regulatory (P4). For GE crop development, Calyxt (2019) refers to the phases of development as: Trait Discovery (D), Creation of Genome-Edited Lines (P1), Field Evaluation and Testing (P2), and Seed Production (P3). GE technology development differs slightly from GM. While the adjectives used to describe these phases differ across firms, the general sequence of R&D phases are similar to what is described here. Details of costs, duration, and probability of success for each of these phases are described in a later section.

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[2] The technical development of GE products is not covered here but is described in detail in Prado et al. (2014) and Jaganathan et al. (2018).

Wheat is one of the large-acre crops for which technological development has recently been lagging. Partly in response to the demand for new technology, there have been efforts primarily in Australia and the United States for development of GM wheat. In Australia, GM wheat for drought tolerance was being developed by DEDJTR (Department of Economic Development, Jobs, Transport and Resources) and CSIRO (Commonwealth Scientific and Industrial Research Organization). According to the Australian Government Office of the Gene Technology Regulator (OGTR)[3] there were 19 applications made since 2005 for GM wheat field trials, with 7 of these still current and 3 focusing on drought tolerance. These trials are evaluating several traits including abiotic stress (drought, heat, salt, aluminum), altered grain composition, increased yield and yield stability, nitrogen use efficiency, and resistance to fungal disease.

DEDJTR was granted a license to plant GM wheat at the Victorian government research station site in Horsham between 2013 and 2016. The purpose of the trial was to evaluate the wheat yield under field conditions. Like the DEDJTR GM canola, the GM wheat uses the delayed leaf senescence technology, "LXR™", to enhance yield and drought tolerance (OGTR 2013). There were two treatments in Horsham (rainfed and irrigated). DEDJTR has since been granted another license to plant GM wheat in Horsham to evaluate wheat that was been genetically modified for enhanced nitrogen use efficiency and water use efficiency.

There has also been GM trait development in wheat in the USA and China and, in both countries, there has been research on drought tolerance. In the USA since 1998, there have been about 550 GM wheat field trials and approximately 30 of these have focused on drought tolerance[4]. In China, 62 regulatory applications were made for GM wheat between 1997 and 2009 and 18 of these were for drought resistance. Four cases were authorized for environmental release covering drought resistance, disease resistance to yellow mosaic virus, pre-harvest sprouting resistance and dough strength for quality improvement (Xia et al. 2012). Out of 105 gene sequences or technologies used for GM wheat pending patents in China by the end of 2010, 73 were abiotic stress-related. Eight out of 33 papers published by Chinese researchers on GM wheat were related to abiotic stresses and five of these to drought resistance. These figures indicate that despite a strong focus on drought resistance during pretrial research, these traits are not authorized for field trials and their performance is not reported as frequently as for other traits. Finally, a GM trait for rust resistant is under development by the University of Minnesota working with CSIRO[5].

In 2009, nine producer and miller organizations in Australia, the United States, and Canada publicly gave their support to innovation in wheat, including biotechnology commercialization (U.S. Wheat Associates 2009). In 2014, these groups plus seven additional groups re-confirmed

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[3] OGTR. "Table of applications and authorisations for Dealings involving Intentional Release (DIR) into the environment." Australian Government, Department of Health, Office of the Gene Technology Regulator. Available at: https://www1.health.gov.au/internet/ogtr/publishing.nsf/Content/ir-1 [Accessed in 2016].

[4] USDA-APHIS. "Notifications." USDA - Animal and Plant Health Inspection Service. Available at: https://www.aphis.usda.gov/aphis/ourfocus/biotechnology/permits-notifications-petitions/notifications [Accessed in 2014].

[5] The wheat rust project is being managed operationally by the John Innes Institute. See Stuchbery (2019) and background in http://2blades.org/projects-and-technology/projects/1/ and http://2blades.org/our-team/people/dr-roger-freedman/. The Blades Foundation is a foundation based in Chicago.

their support with a new pledge for further innovation in research in wheat, including advanced breeding and biotechnology (U.S. Wheat Associates 2014). The groups also support science-based regulatory systems and synchronized commercialization of biotech traits in the three countries.

A number of popular articles have summarized GE as a technology and how it may impact crop development (e.g., Barber 2019). Due to the newness of GE as a technology, many of the traits are under development and we provide a description of those focused on wheat below. [6]

The companies that are currently working on GE wheat include Calyxt, Arcadia, YTEN, and UKKO. These are in addition to the major agricultural biotech companies. Arcadia appears to be the most prolific and has targeted traits in wheat that include high fiber, reduced gluten, and extendable shelf-life. Calyxt is working on multiple crops and for wheat, they list high-fiber and herbicide tolerance as targeted traits. YTEN lists yield improvement in wheat as a targeted trait along with increased biomass. UKKO is an early-stage food biotech start-up trying to solve food allergies and sensitivities using GE technologies. They are targeting wheat and peanuts, to be followed by sesame, soy, and milk. Finally, GE wheat with traits to control weeds has been targeted by Chinese scientists (Zhang et al. 2019; Chinese Academy of Sciences 2019).

Presumably all of the major agbiotechnology companies are working on adopting gene editing into their programs. Dow-DuPont has the most patents, followed by Monsanto. Taylor (2019) provides a selected list (not exhaustive) of companies using CRISPR to improve crops. These include Benson-Hill (row crops), Corteva (waxy corn), Pairwise (corn, soybean, fruits and vegetables), Syngenta (corn, soy, wheat, tomato, sunflower), Topic Biosciences (bananas, decaffeinated coffee) and Yield10BioScience (Camelina) Monsanto's efforts, through its acquirer Bayer Crop Science indicated (Bayer Crop Science 2018, p. 52) their intended use of Pairwise Plants (which was an investment target of Monsanto). Pairwise Plants will work exclusively with Bayer on gene editing of corn, soybeans, wheat, cotton, and canola. Pairwise Plants (https://pairwise.com/partnership/) is also working with Monsanto Growth Ventures. These agreements were apparently made prior to the Bayer-Monsanto merger. They seem to be a trait company using GE (using the CRISPR approach) for editing.

Other crops being modified with GE are mentioned briefly here. Calyxt is currently developing high oleic soybeans, high oleic/low linolenic soybeans, and improved quality alfalfa (Calyxt 2017). Arcadia is currently developing high quality and drought tolerant soybeans, safflower that is high in omega 3 and 6 oils, rice, and cotton. CIBUS has developed a herbicide tolerant canola and is developing GE traits in canola, wheat, rice, flax, potato, corn, peanut and soybean. Finally, Benson-Hill is working on numerous traits (Stephens Market Research 2019), typically referred to as 'output' traits which seek to alter the quality or consumer characteristics of the crop. They are working directly with food and beverage companies to develop tailored traits including in barley (Anheuser-Busch InBev) and cocoa (Mars, Inc.). In most of these cases, the GE development is targeted towards crops or traits that are more differentiated and/or with a

[6] Many traits in wheat for market entry with a GE product are quantitative in nature and would be more difficult to edit.

smaller potential growing area (in total acres or hectares) than those targeted using GM technology.

Role of Regulations

A fundamental feature of new crop varietal development relates to the regulatory mechanism governing the commercialization of new crop traits and/or varieties. It is important to note that, for GM traits, almost all countries have mechanisms of approval prior to commercialization. The costs related to regulatory approval vary substantially depending upon requirements in the individual countries, and, in general, these are costly, time consuming and non-harmonized across the individual countries.

For GE traits and crop development, most countries allow for commercializion without requiring regulatory approval. In the United States (USDA 2018) it was announced early that GE crops would not be subject to regulatory approvals.[7] Specifically, the announcement indicated that

> *USDA does not regulate or have any plans to regulate plants that could otherwise have been developed through traditional breeding techniques as long as they are not plant pests or developed using plant pests. This includes a set of new techniques that are increasingly being used by plant breeders to produce new plant varieties that are indistinguishable from those developed through traditional breeding methods. The newest of these methods, such as genome editing, …"*

Australia is another major anticipated producer of GE crop and, in 2019, the Australian government clarified their approach to regulation of GE crops. Specifically, it was indicated that GE technology would not require regulatory approval for developments in plants, animals, and human cells that are shown to not introduce new genetic material (Mallapaty 2019). This decision was scheduled to take effect on October 8, 2019.

Japan also decided not to impose regulatory approval on GE crops. This contrasts with Japan's current regulations on GM crops which are onerous, although manageable (Normile 2019a; Normile 2019b).[8] This decision is critical because Japan is a major importer of most grains and this decision may set a precedent for other importing countries.

A major governmental body that requires regulatory approval for GE crops is the European Union (EU). Specifically, the EU determined on July 25, 2019 (EU Court of Justice 2018) that EU member states must regulate both the import and planting of GE food and agricultural products similar to that of GM crops.

Taken together, the evolution of national and regional regulations will have important impacts upon the global development of GE crops. The geopolitical balance of forces regarding regulation of GE crops is currently promising. This is partially based on the fact that, in recent years, China has massively invested in biotechnology, while the EU has suffered from

[7] These are described in detail in USDA-APHIS (2018) for the United States.
[8] The decisions for the Japanese GE regulations are in and in USDA-FAS (2019a and 2019b).

disinvestment, especially in agricultural biotechnology as a consequence of the backlash against genetically modified organisms (GMOs). In responding to the dichotomy in regulatory costs, Stephens Market Research (2019) suggested that while GM is hugely expensive, the technology is only applicable to large area crops, and/or for traits that have substantial value on a per acre basis. In contrast, GE technology has a greater applicability to smaller area crops and/or niche traits. This is due to the lower cost in both time and money for GE crop R&D which is, in part, due to the absence of costs (time and money) related to regulatory approval.

Market Valuation Using Real Options

The empirical model in this study uses the real option framework to provide market valuation of potential research and development (R&D) projects. The model builds on previous studies using real options to value investments in R&D (Brach and Paxson 2001; Jensen and Warren 2001; Luehrman 1998; Morris, Teisberg and Kolbe 1991; Seppä and Laamanen 2001) and on the use of real options to value GM traits in crops (Carter, Berwald and Lyons 2005; Flagg 2008; Furtan, Gray and Holzman 2003; Wilson, Shakya and Dahl 2015; Shakya, Wilson and Dahl 2013; Wynn et al. 2017; Wynn et al. 2018).

Valuation that takes into account embedded real option values has distinct advantages relative to the exclusive use of traditional discounted cash flow (DCF) models. Most R&D projects that span a period of time typically have embedded options at each phase of the project development (Dixit and Pindyck 2012). The inability of DCF to capture management flexibility and dynamic investment decisions is a drawback and suggests that DCF is likely to underestimate the value of these types of investments (Trigeorgis 1995) by failing to account for the value of management flexibility offered by the ability to defer decisions to a later date. This is because DCF assumes that the decision maker is totally committed to their initial investment decision without any flexibility to change at a later date.

The foundations of real options analysis are summarized in Schwartz and Trigeorgis (2004) who describe the evolution of this method and its role in valuing R&D. Features of the problem that are important include: 1) uncertainties are resolved through time, and 2) managers have options that can be exercised throughout the duration of the project. In particular, investments in R&D generally provide the option to continue or abandon at each stage of the process. Investing in R&D is equivalent to buying a call option and can be valued as a real option because it involves future opportunities, uncertainty, and exercisable options. Earlier work on this methodology includes Luehrman (1998) and Morris et al. (1991) which contain descriptions as to why real options can be used to model R&D. Bogdan and Villiger (2010) provide a summary of the use of real options for valuing projects in the life sciences.

One of the primary real options that is implicit in almost all R&D projects is the option to abandon which has been described in detail in the literature (Berger, Ofek and Swary 1996; Dixit and Pindyck 2012; Kodukula and Papudesu 2006). The abandonment option is equivalent to an American put option. Simply, at each phase, the developer has the option to abandon a project which would typically be the case if the discounted value of payoffs from continuing to the next phase are lower than a specified *salvage value*. The salvage value represents the current value of project assets that can be sold off and/or licensed to a third party. The abandonment option is in-the-money if the salvage value (i.e., strike price) exceeds the discounted future project value and out-of-the-money otherwise. Per conventional option pricing theory, the value of abandonment option increases with the volatility of net returns and with the salvage value (strike price) of the project.

Early studies that used real options to value GM wheat (Carter et al. 2005; Furtan et al. 2003) were primarily focused upon a real option that could only be excercised at the end of the commercialization period (i.e., a European style option). Therefore, the values could be derived using the closed-form Black-Scholes option pricing model commonly used in financial markets. Later approaches used in valuing GM traits in crop development (Shakya et al. 2013; Wilson et al. 2015; Wynn et al. 2017; Wynn et al. 2018) differ from this earlier approach in that the real option valuation is applied throughout the R&D and commercialization stages of development (i.e., an American style option) using the binomial lattice approach to deriving the option value.

EMPIRICAL MODEL

To compare the economics of GE versus GM crop technology, a real option valuation (ROV) model for the option to abandon was constructed in Microsoft Excel[9] using the *@Risk*[10] and *PrecisionTree*[11] add-ins. Both add-ins are part of the *PrecisionTools* suite of applications sold by Palisade Software. The @Risk application allows the user to embed Monte Carlo simulation models into an Excel spreadsheet. The PrecisionTree application allows the user to embed decision trees into an Excel spreadsheet. Both add-ins can be used together to create simulated decision trees which is how they are employed in the model.

The metric used in comparing GE versus GM technologies is the required potential cropping area (in acres) at which the developer of the new crop variety could expect to achieve a breakeven economic valuation on their long-term R&D investment. This value is obtained by setting the mean of the simulated ROV distribution equal to zero and then solving for the potential cropping area which is a user input variable in the model. Therefore, the economic metric basically answers the question of how big the potential market has to be (in acres) before it becomes economically feasible for the research firm to begin development of the proposed GE or GM crop. To solve for the breakeven crop area, the stochastic goal seek feature of @Risk is used. This feature is similar to Excel's standard goal seek feature; however, it allows the user to constrain the simulation statistic of a particular output cell rather than the cell value itself.

Most contemporary texts on ROV applied to projects (Bogdan and Villiger 2010; DiLellio 2018; Guthrie 2009; Kodukula and Papudesu 2006; Mun 2016; Razgaitis 2009; Trigeorgis 1995) generally list four general methods for calculating real option values: (1) closed form option pricing formulas, (2) Monte Carlo simulation, (3) lattices, and (4) decision trees. The first two

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[9] Microsoft Corporation. 2019. Microsoft Excel 2019.
[10] Palisade Software. 2018. @Risk: Advanced Risk Analysis for Microsoft Excel and Project. Palisade Software, Inc. Available at: www.palisade.com/risk/.
[11] Palisade Software. 2018. PrecisionTree: Decision Analysis Add-in for Microsoft Excel. Palisade Software, Inc. Available at: https://www.palisade.com/precisiontree/.

methods generally work best when the option has a fixed exercise date (i.e., is a *European* option). The latter two methods are flexible enough to be applied to options that have a variable exercise date (i.e., is either a *Bermudan* or *American* option). Since most real option applications involve variable exercise, the binomial lattice and decision tree methods are the most commonly applied.

When comparing lattice to decision tree models for ROV modeling there are two primary differences (Kodukula and Papudesu 2006): (1) decision tree models can account for both private and market risks while lattice models address only market risks, and (2) decision trees account for project risks through the probability of a limited set of mutually exclusive outcomes while lattices can account for a much wider range of outcomes through the discretization of the underlying stochastic process based upon the user-specified step size. Also, there is no general agreement in the finance community regarding the appropriate discount rate to use for decision trees while the risk-free rate is the established discount rate used in lattices. Another potential drawback of decision trees (versus lattices) is that the probabilities of outcomes have to be estimated (potentially using subjectivity) while the probabilities for lattice outcomes are driven completely by the underlying stochastic process.

Most R&D projects involve a combination of both market and non-market driven processes. In particular, a typical project can be broken down into two major phases: (1) the actual research and development (R&D) activities conducted in the development of the potential product, and (2) the commercialization of the product provided it successfully completes the full R&D process. The first phase is generally characterized by non-market processes that are related to the probability of success or failure of each research stage. The second phase is generally driven by a market-driven process based upon the product's sales penetration into the target marketplace and the subsequent returns generated.

The empirical model used in this study is unique in that it combines both a decision tree and a binomial lattice to calculate the market value of a potential R&D project. A simple schematic of the decision-theoretic model employed in this study is illustrated in Figure 1. The commercialization phase is modeled as a binomial lattice with an option to abandon. The ROV from this binomial model becomes the value for the final decision node in the tree where the decision is whether to proceed to commercialization following the successful completion of the final R&D phase of development.

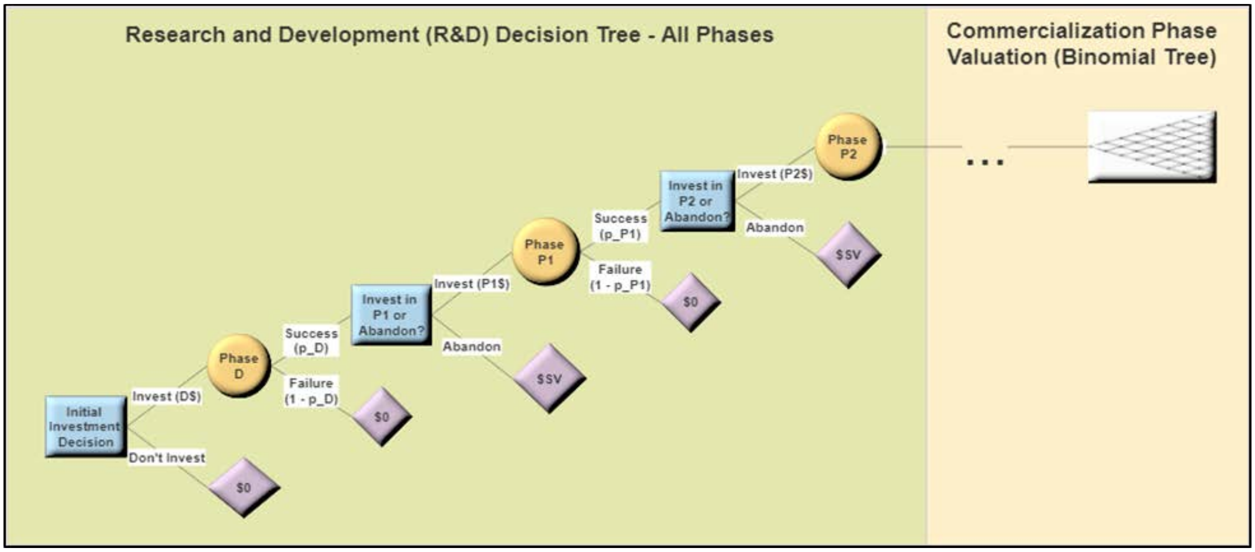

Figure 1. Decision-Theoretic Schematic of the Empirical Model

Each R&D phase is modeled in a two-step process. First, a chance node is used to model the success or failure in completing the particular R&D phase. If the chance node results in failure, the decision tree is terminated with a zero payoff at the terminal node. If the chance node results in success, the decision maker (R&D firm) proceeds to the following decision node where the decision is either: (1) to continue on to the next R&D phase (with subsequent investment) or (2) exercise the option to abandon and receive the specified salvage value on the project at that stage. If the decision is to continue to the next R&D phase, the decision maker would invest the full research cost for the next phase. Therefore, the decision node would be decided by the maximum of either the discounted project value at that point of decision (adjusted by the additional research cost investment) or the salvage value. If the salvage value is higher, the option to abandon will be exercised.

Each R&D phase is stochastically modeled using three parameters: (1) the total research cost, (2) the total time to completion, and (3) the probability of successful completion. The total research cost (in million $) and time to completion (in years) are modeled as continuous random variables in the model using a PERT distribution. The PERT distribution is one of several subjective distributions provided in @Risk (others include the uniform and triangular distributions) and is characterized by a minimum, most likely (mode), and maximum value. The PERT is a transformation of the four-parameter beta distribution with the additional assumption that its expected (mean) value (μ) is equal to $(a+4b+c)/6$ where a is the minimum, b is the mode, and c is the maximum value. Figure 2 illustrates three examples of the PERT distribution with varying parameter values. The probability of successful completion of each R&D stage is treated in the model as a fixed input.

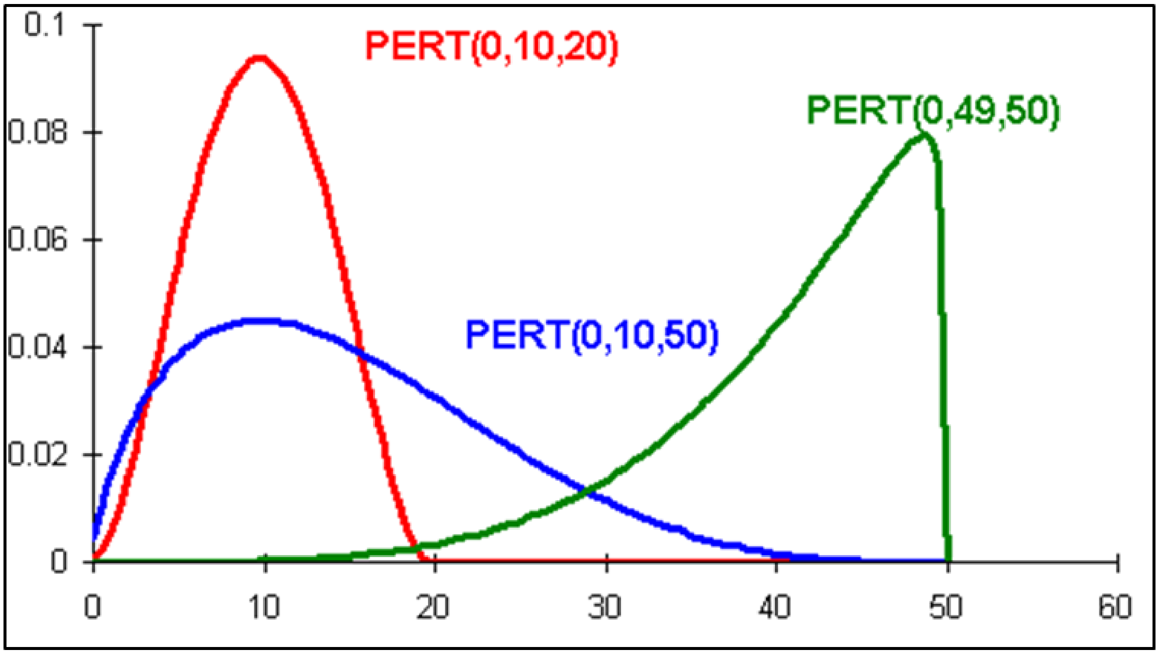

Figure 2. Three Examples of the PERT Distribution with Varying Parameter Values

The commercialization phase is modeled as a binomial lattice with the option to abandon future sales of the product at any time during the 15-year commercialization period. Solving the binomial lattice model is essentially a three-step process: (1) calculate the project net present value (NPV) using traditional discounted cash flow analysis, (2) calculate the projection lattice using the calculated up and down step values, and (3) calculate the valuation lattice by working backwards through the projection lattice and overlaying the option decision rule. The following text provides further detail on this process.

Figure 3 illustrates the calculation of the projection lattice for a real option model using 3 projection steps for illustrative purposes. The initial NPV value is calculated using standard discounted cash flow analysis. In this study, the discount rate used for calculating this initial NPV value is the firm's *weighted average cost of capital* (WACC). The projection lattice uses a standard up-step value (u) and down-step value (d) which are calculated using the annualized volatility (σ) of the sample returns used in calculating the project NPV. The formulas for the up- and down-steps are:

$$u = e^{\sigma \cdot \sqrt{\Delta t}}, \tag{1}$$

$$d = e^{-\sigma \cdot \sqrt{\Delta t}} = \frac{1}{u}, \tag{2}$$

where Δt is the step-size in years.

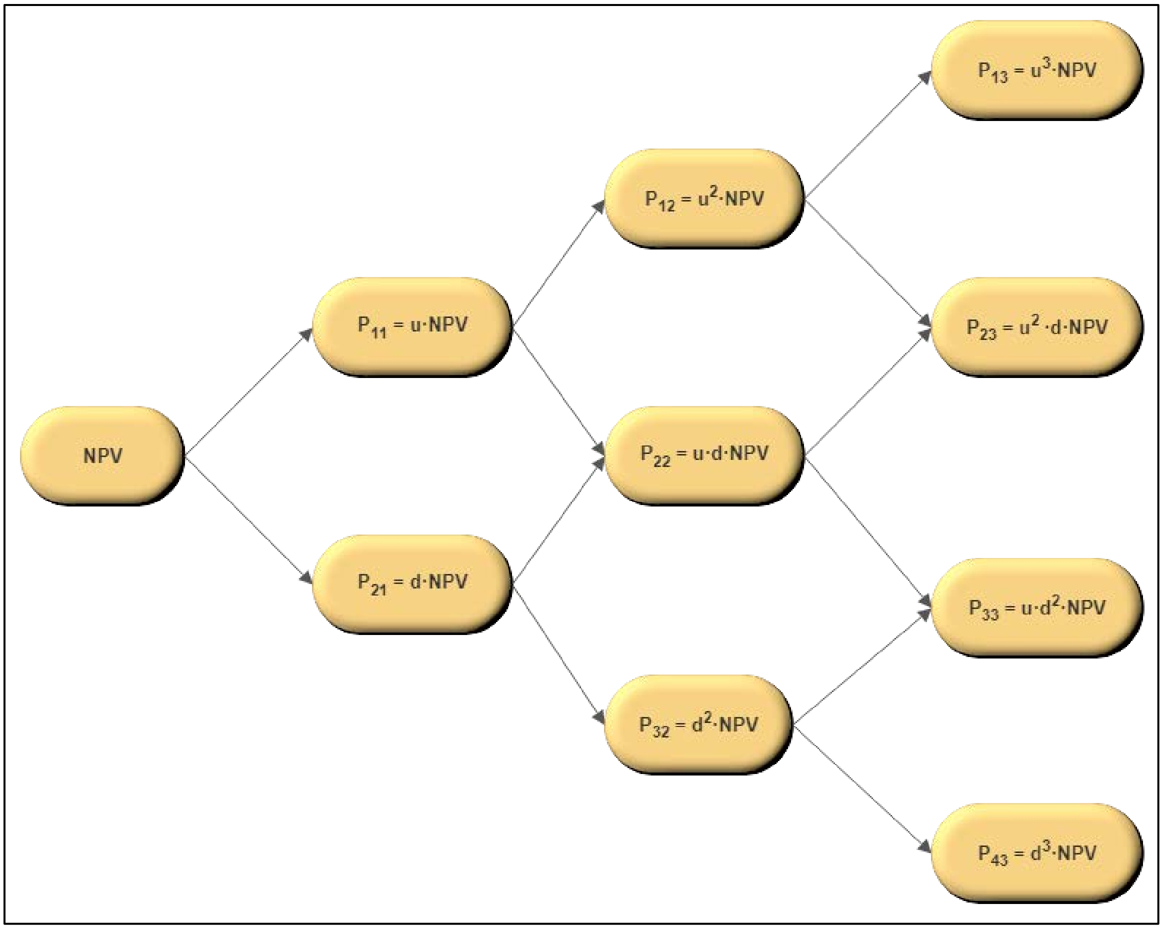

Figure 3. Projection Lattice for Abandonment Option (3 Forward Steps for Illustration)

Figure 4 illustrates the calculation of the valuation lattice for the abandonment option. The calculation starts with the end nodes where the value is the maximum of either the projection matrix value or the salvage value. If the salvage value is larger, it is assumed that the option to abandon would be exercised.

From the end nodes working backward, the option rule compares a calculated discounted valuation to the salvage value and takes the maximum of the two values. The discounted valuation is calculated recursively by the following formula:

$$V_{i,j} = e^{-r\cdot\Delta t}\cdot\left[p\cdot V_{i,j+1} + (1-p)\cdot V_{i+1,j+1}\right], \tag{3}$$

where r is the risk-free interest rate, Δt is the time step size, and p is the risk-neutral probability value calculated as

$$p = \frac{e^{r\cdot\Delta t} - d}{u-d}. \tag{4}$$

Note that both the projection and valuation lattices can be calculated as zero-based, upper triangular, symmetric matrices where the project stages are represented by the column subscripts

$(j = 0,\ldots,T)$ and the project states are represented by the row subscripts $(i = 0,\ldots T)$ where T is the total number of projected stages. This makes it easy to incorporate binomial lattices into spreadsheet models.

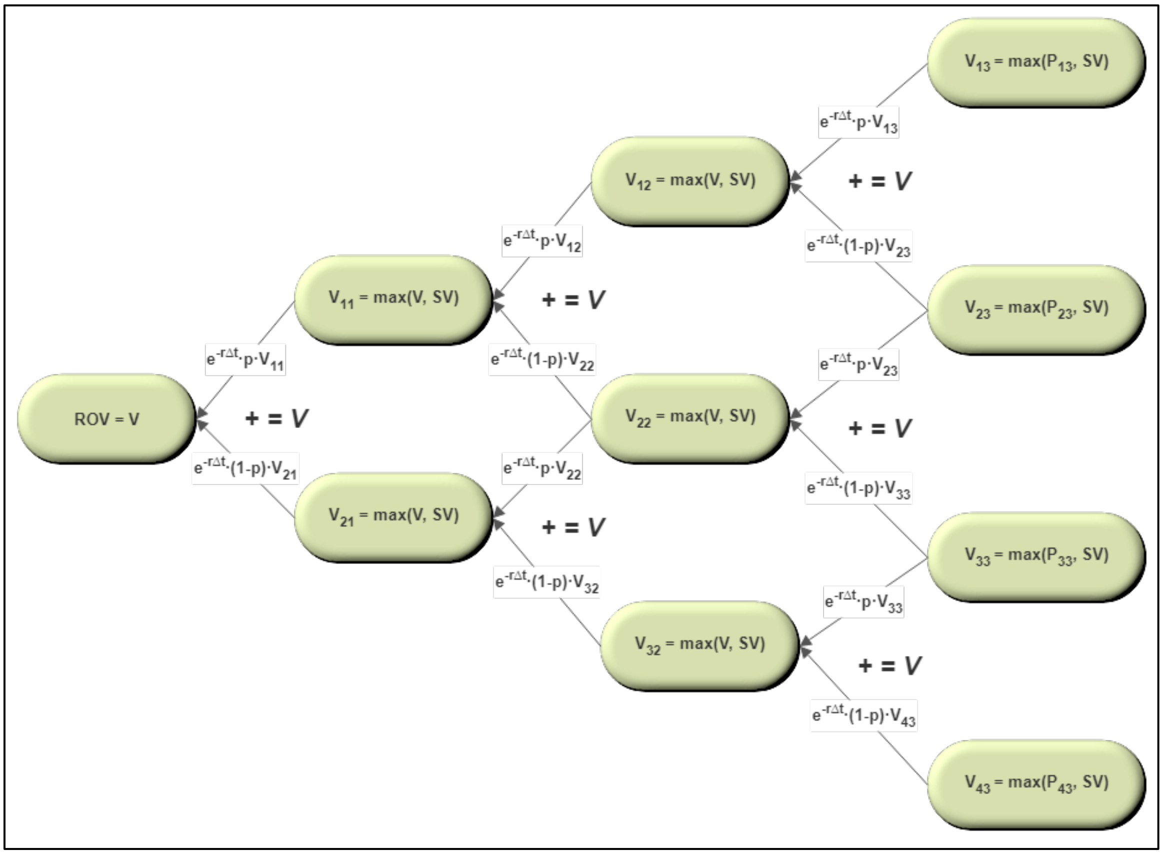

Figure 4. Valuation Lattice for Abandonment Option (3 Forward Steps for Illustration)

The modeling of the commercialization cash flows over the fixed 15-year commercialization period are based upon a *market penetration model* similar to those commonly used in the pharmaceutical industry (Bogdan and Villiger 2010), and in earlier studies on GM crops (e.g., Wilson et al. 2015; Shakya et al. 2013; Wynn et al. 2017; Wynn et al. 2018). The maximum market area (in million acres) is an entered parameter in the model and is fixed over the entire 15-year period. The model assumes that the particular GE or GM crop achieves its maximum market penetration, measured as a percentage of the maximum market area, in Year 8 of commercialization. This percentage is assumed to be stochastic and is modeled as a uniform distribution in @Risk. Typically, most patents expire after 8 years; therefore, Year 8 is chosen as the peak sales year.

The beginning (Year 1) and endpoint (Year 15) market penetration factors are modeled as a percentage of the maximum Year 8 percentage and are stochastically modeled using uniform distributions. The intervening years' (Years 2-7 and 9-14) market penetration percentages are calculated using linear interpolation between the simulated values.

The firm's gross return per acre sold is measured by the trait value per acre (θ) and the percentage (τ) of the trait value retained by the technology firm. This value is exogenous as there are few GE traits in commercialization and for which trait values are available. Hence, this is an assumption and sensitivities are evaluated. The firm receives τ·θ in gross revenue per acre of sales while the producer retains (1 – τ)·θ in benefits from adopting the technology. In the empirical model, it is assumed that θ is a user-input into the model and that τ is equal to one. Therefore, θ is assumed to be the total trait value as measured as the technology firm's share.

The user-input value of θ is assumed to be in current dollars; therefore, it is necessary to account for inflation (ρ) in the projected value of θ which is assumed to be constant and input by the user. Therefore, the research firm's gross sales revenue (*G*) in year *t* of commercialization can be calculated as

$$G_t = \rho^{\tilde{T}+t} \cdot \theta \cdot \tilde{\lambda}(t) \cdot A, \tag{5}$$

where T is the stochastically determined length of all R&D phases, θ is the user-input trait value per acre (in current dollars), λ(t) is the stochastically determined market penetration percentage, and *A* is the user-input maximum market acreage for the prospective GE or GM crop.

To calculate net revenue per acre, the firm's costs per unit of sales such as seed production, marketing, supply chain, and other costs must be accounted. In the empirical model, a simple net margin percentage (ψ) is used to account for these costs and is stochastically generated using a uniform distribution. Therefore, the technology firm's net revenue (R) per acre in year *t* of commercialization can be calculated as

$$R_t = \tilde{\psi} \cdot G_t. \tag{6}$$

All of the values in the R&D and commercialization models are discounted back to current value at time period 0 which is prior to initiation of the first R&D phase. The R&D costs are discounted using the risk-free interest rate while commercialization net returns and salvage values are discounted using the firm's WACC value.

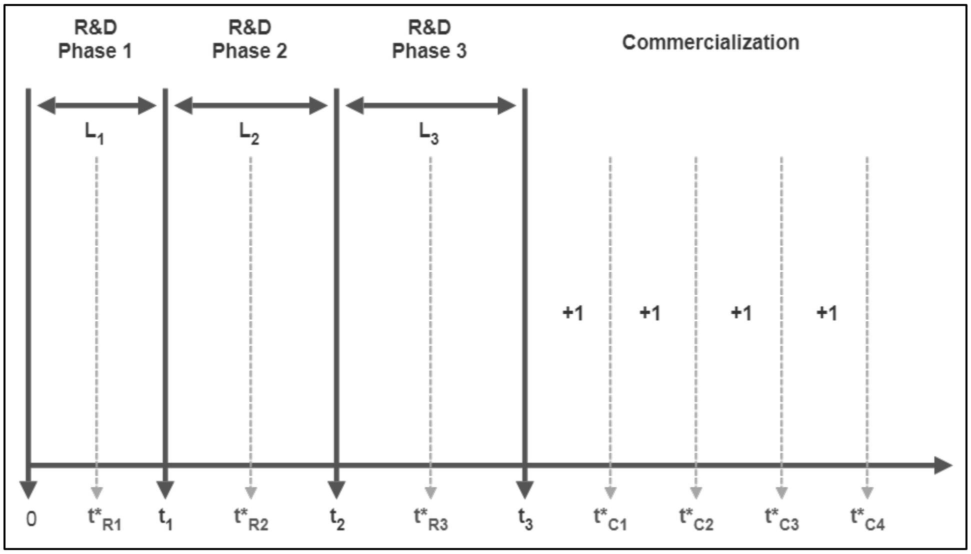

Figure 5. Determination of Discount Time Values in Empirical Model Using 3 R&D Phases

The procedure for determining the time values in the empirical model is graphically illustrated in Figure 5 using a timeline with 3 R&D phases as an example. Each R&D phase *i* has a stochastic length of time to completion (L_i) determined by the PERT distributions. The mid-point (t^*_{Ri}) of each phase is used to discount the research costs associated with each phase since it is assumed that these costs are expended continually over the phase. The R&D salvage values are discounted at the end of each R&D phase (t_i) since this is the point at which the option decision must be made. For the commercialization annual periods, the discounting occurs at the end of the period; however, the time value would also be stochastic and dependent upon the total time required to complete the R&D phases (t_3 in the example). Therefore, for year *t* of commercialization, the net revenue per acre (R_t) would be discounted using T+t as the time value where T is the total length of the R&D phases.

The procedure for calculating the ROV from the empirical model uses the following 3 basic steps. First, the random parameter values are drawn from the statistical distributions and are inserted into the spreadsheet model. Second, the commercialization phase ROV value is calculated from the binomial lattice model and is inserted into the final decision node of the decision tree (the decision to proceed with commercialization). Third, the decision tree model is used to calculate the ROV valuation prior to initiation of R&D on the project.

The Monte Carlo simulation procedure generates a distribution of ROV valuations from the model. The required market acreage to breakeven on ROV is solved by setting the mean of the ROV simulated distribution to zero and using the @Risk stochastic goal seek function to find the maximum crop area (*A*) that achieves the breakeven ROV.

One of the advantages of using the decision tree representation of the R&D process is that the conditional distributions given success at each phase of the R&D process can be directly derived from the tree model. For example, the model can directly provide the conditional mean ROV value given that the initial R&D phase (Trait Discovery) was successful.

DATA SOURCES AND DISTRIBUTIONS

Data on the standard research phases along with the costs, duration and probability of success for each phase of GE and GM crop research and development were obtained from personal interviews with industry experts supplemented by surveys. A set of 8 firms known to be involved in GE and GM trait development were identified. These included some the larger agbiotechnology companies, as well as some of the newer companies and some were in the U.S., and others off-shore. Because of the sensitivity of the data, survey respondents are kept anonymous. A set of questions were developed and sent to the targeted individuals, which was followed by a phone call to elicit and clarify their response. Due to the relative newness and uncertainty surrounding GE technology, respondents were asked for their input on the minimum, most likely and maximum values of the model parameters rather than for specific point estimates. These were then incorporated into our simulation model as described below.

The parameter values for the R&D process for GM crop development are shown in Table 1. Note that the simulation inputs for the GM R&D imply an average time to commercialization (given success at all phases) of 8.0 years with minimum of 6.0 and a maximum of 10.0 years from the initiation of the discovery phase until the beginning of commercialization. Provided success at all phases, the average total R&D costs for GM amounts to $80.7 million with a minimum of $52.0 million and a maximum of $128.0 million.

Table 1. Research and Development Model Parameters for GM Crop Development

Phase	Description*	Time (Years)	Cost (mil $)	Probability of Success
D	**Trait Discovery**	1 (Non-Stochastic)	PERT(2.0, 3.5, 8.0)	5%
P1	**Proof of Concept**	PERT(1.0, 1.5, 2.0)	PERT(5.0, 7.5, 12.0)	25%
P2	**Early Development**	PERT(1.0, 1.5, 2.0)	PERT(10.0, 12.5, 18.0)	50%
P3	**Advanced Development**	PERT(1.0, 1.5, 2.0)	PERT(15.0, 22.5, 40.0)	75%
P4	**Regulatory Submission**	PERT(2.0, 2.5, 3.0)	PERT(20.0, 30.0, 50.0)	90%

**Source*: Bell and Shelman (2006).

The parameter values for the R&D process for GE crop development are shown in Table 2. For GE R&D, the average time to commercialization is 5.5 years with a minimum of 4.0 and a maximum of 7.0 years from the initiation of discovery until commercialization. The average total R&D cost is $13.3 million with a minimum of $8.0 million and a maximum of $24.0 million.

Table 2. Research and Development Model Parameters for GE Crop Development

Phase	Description*	Time (Years)	Cost (mil $)	Probability of Success
D	**Trait Discovery**	1 (Non-Stochastic)	PERT(2.0, 3.0, 6.0)	25%
P1	**Creation of Genome Edited Lines**	PERT(1.0, 1.5, 2.0)	PERT(2.0, 3.0, 6.0)	50%
P2	**Field Validation and Testing**	PERT(1.0, 1.5, 2.0)	PERT(2.0, 3.0, 6.0)	75%
P3	**Seed Production and Pre-Launch**	PERT(1.0, 1.5, 2.0)	PERT(2.0, 3.0, 6.0)	90%

***Source**: Calyxt (2019).

Note that there are three major differences when compared to the GM assumptions:

1. The GE R&D process is one stage shorter in that it lacks a regulatory approval stage (P5). This is because GE traits do not, in general, require regulatory approval in most countries with the exception of the European Union.
2. The probability of success during the discovery phase (D) is much higher for GE (25%) when compared to GM (5%).
3. The average R&D costs for GE are substantially lower – particularly for all phases beyond discovery (D).

For both technologies, the successful completion of all R&D phases leads to the commercialization of the variety where it is made available to the market. Note that the odds of successfully reaching a particular R&D phase (beyond D) is equal to the product of the probabilities of the preceding phases. Figure 6 shows the cumulative odds of successfully reaching each stage of development in the R&D process. Due to the very low odds of success during the trait discovery phase (D), the odds of a GM variety reaching the market is very low (0.42% or approximately one out of 238 odds). On the other hand, for GE, the much higher probability of success in the D phase leads to a much higher odds of the variety reaching the marketplace (8.44% or approximately one out of 12 odds).

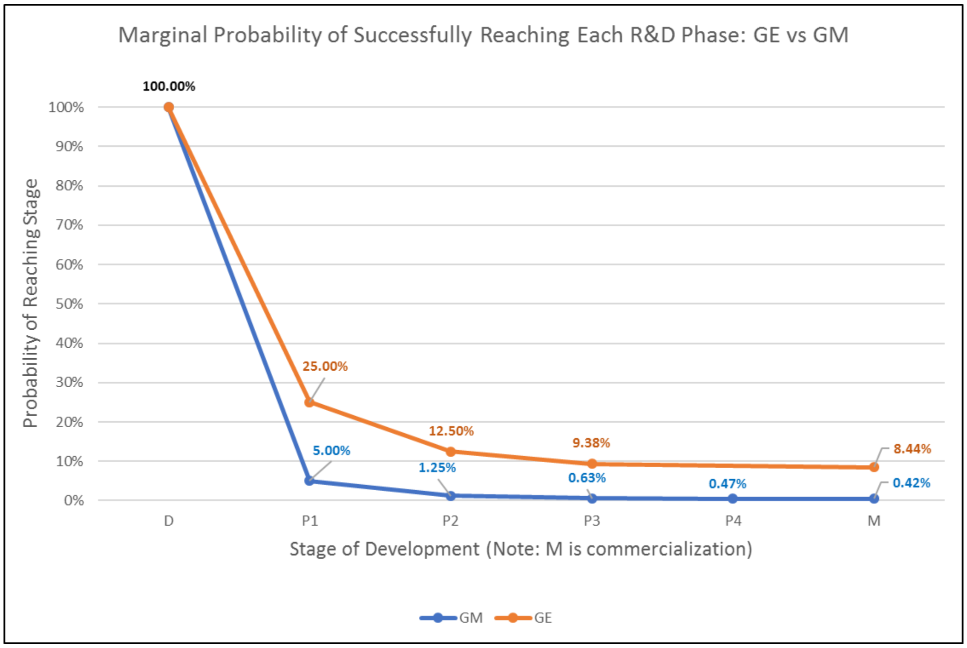

Figure 6. Marginal Probability of Successfully Reaching Each R&D Phase: GE versus GM

With the exception of solving for the total available area via the @Risk goal seek to derive the economic comparison metric, the commercialization phase parameters are identical between the GE and GM crops (Table 3). These are by *a priori* assumption. In addition to these parameters, the model assumes a risk-free interest rate (*r*) of 3 percent and a firm weighted average cost of capital (WACC) with a base value equal to 15 percent annual. Salvage values were set as a multiple of cumulative sunk R&D costs with a base multiple set at a value of two. The values for these parameters were set after consultation with industry experts. In the results to follow, some of these parameter values will be varied above and below their base values to examine the sensitivity and robustness of the model results with respect to these parameter values.

Table 3. Commercialization Phase Parameter Assumptions for Both Models

Variable	Value
Total Available Area in Million Acres (*A*)	Solved by Model Using @Risk Goal Seek
Max Market Penetration [λ(8)]	Uniform (50%, 90%)
Initial Market Penetration [λ(1)]	Uniform (50%, 100%) x λ(8)
End Market Penetration [λ(15)]	Uniform (50%, 100%) x λ(8)
Trait Value per Acre (Θ)	Input by User (Base = $25)
Tech Firm Share of Trait Revenue (τ)	Fixed at 100%
Tech Firm Margin After Costs (ψ)	Uniform (40%, 60%)
Inflation Rate (ρ)	1.5% annual

The market penetration profile during the commercialization phase for both GM and GE varieties is shown in Figure 7. The red line represents the percentage at the means of the simulated distributions for years 1, 8, and 15. The green line represents the profile is all of the simulated distributions are at their maximums while the yellow line shows the profile if all of the distributions are at their minimum values. Therefore, the green and yellow lines provide boundaries on the potential values in each year of commercialization.

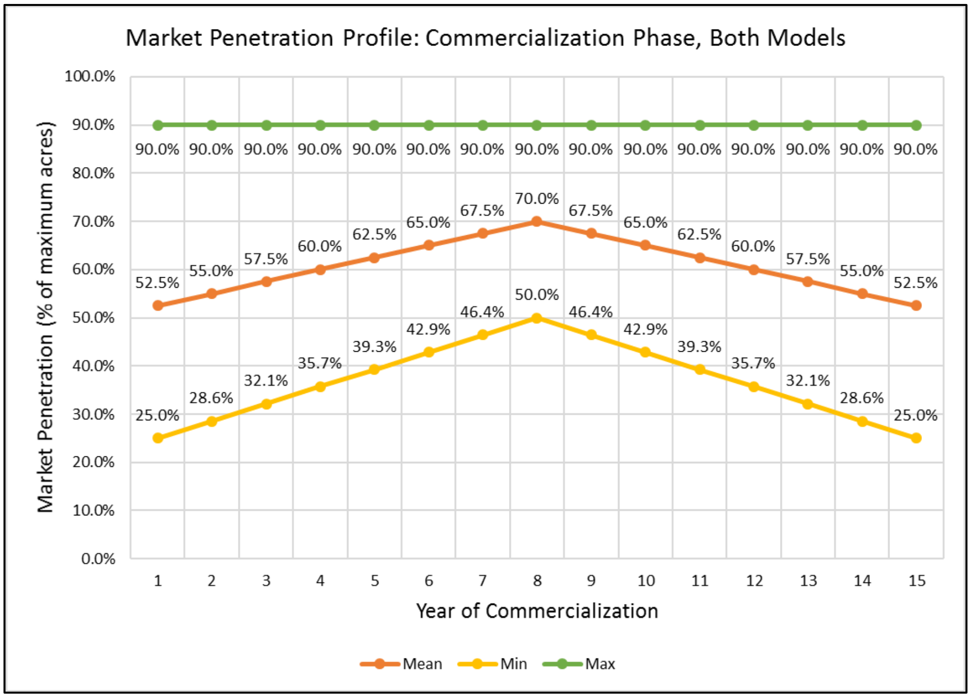

Figure 7. Market Penetration Profiles Under Mean, Maximum, and Minimum Scenarios

MODEL RESULTS

The base simulation scenario assumes a $25 per acre trait value (developer's share). Additional scenarios where the trait value ranges from $5.00 to $50.00 per acre were also run with the results summarized in Figure 8. At the $25 per acre baseline scenario, the minimum required acreage was 62.3 million acres for a GM variety and 2.3 million acres for a GE variety with the same commercialization parameters. Across all trait values that the minimum required acreage for GE was constantly 96.3% less than the required acreage for a GM variety with the same commercialization profile. Also, the minimum required acreage for both varieties can be represented by a deterministic (R^2 =1) power function fit which explains the constant percentage reduction in the required acreage.

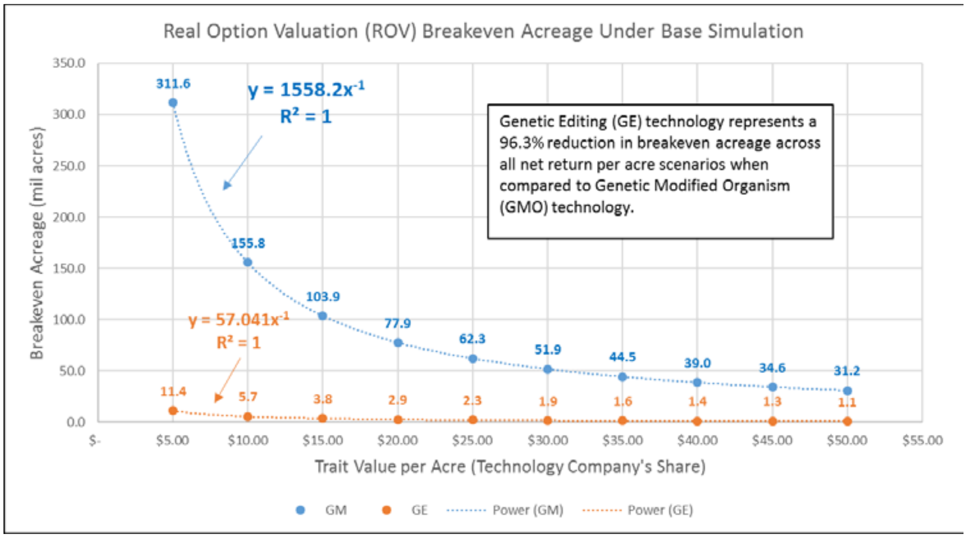

Figure 8. ROV Breakeven Acreage Values for GE and GM Crops Under Varying Trait Values

Additional sensitivities were run for the following model parameters: (1) probability of success for the discovery phase, (2) mean R&D cost for the discovery phase, (3) developer's weighted average cost of capital (WACC), (4) the salvage value multiple of sunk R&D costs, and (5) the annualized volatility of returns during the commercialization phase. Note that the last two sensitivities exclusively affect the value of the real option to abandon. The sensitivity results are summarized graphically in Appendix A and are discussed in this section.

The sensitivity results for GM and GE breakeven acreage to the probability of success in the discovery phase is shown in Figure A-1 and Figure A-2 respectively. As illustrated here, this parameter is one of the more important differences between GM and GE. For GM, the probability ranges from 2 to 10 percent in one percent increments with the baseline value at 5 percent. When dropped to 2 percent, the breakeven minimum acreage increases by 78.2 million acres (from 62.3 to 140.5 million acres). When increased to 10 percent, the acreage declines by 26.0 million acres (from 62.3 to 36.3 million acres). For GE, the probability of success is ranged between 15 to 35 percent in 5 percent increments with a baseline value of 25 percent. When lowered to 15 percent, the minimum breakeven acreage increases by 1.07 million acres (from 2.28 to 3.35 million acres). When increased to 35 percent, the minimum breakeven acreage declines by 0.49 million acres (from 2.28 to 1.79 million acres). Both sensitivity curves are fitted by power functions with high R^2 (greater than 99%) which indicates a greater sensitivity to declines in probability when compared to increases.

The sensitivity results for the mean R&D cost during the discovery phase (maintaining same range from minimum to maximum) are shown in Figure A-3 and Figure A-4 for GM and GE respectively. For GM, the cost is varied from \$2.5 to \$6.0 million in \$0.5 million increments with a baseline value of \$3.5 million. For GE, the cost was varied between \$1.0 to 5.0 million in \$1.0 million increments with a baseline value of \$3.0 million. Both sensitivities had perfect linear fit relationships ($R^2 = 1$) with GM breakeven acreage increasing by 13.1 million acres for every $1.0 million increase in the mean cost while GE breakeven acreage increased by 0.48 million acres for every $1.0 million increase in cost.

The sensitivity results for the developing firm's weighted average cost of capital are shown in Figure A-5 and Figure A-6 for GM and GE respectively. For both GM and GE, the WACC was varied from 10.0 to 20.0 percent at 2.5 percent increments with a baseline value of 15 percent. For GM, a decline in the WACC to 10.0 percent resulted in a 29.3 million acre decline in the breakeven acreage while an increase to 20.0 percent resulted in a 48.9 million acre increase. For GE, a decline in WACC to 10 percent resulted in a 0.93 million acre decline in breakeven acreage while an increase to 20 percent resulted in a 1.38 million acre increase. Both GM and GE sensitivities had very strong fits ($R^2 > 99\%$) to an exponential curve indicating greater sensitivity to increases in WACC as compared to declines.

The sensitivity results for changes in the salvage value multiple of sunk R&D costs are shown in Figure A-7 and Figure A-8 for GM and GE respectively. For both, the multiple was varied from 1.0 to 4.0 in increments of 1.0 with a base value of 2.0. For GM, varying the salvage value multiple had no effect upon the breakeven acreage indicating that salvage values would have to be extremely high in order for the real option value to have any negligible effect upon breakeven acreage. For GE, the multiple has a marginal effect (decline of 0.06 million acres) at 3.0 and a more significant effect when increased to 4.0 (decline of 0.66 million acres).

The effect of increasing the volatility of returns during the commercialization phase is shown in Figure A-9 and Figure A-10 for GM and GE respectively. For both GM and GE, the baseline assumptions resulted in an average annualized volatility of approximately 4.2 percent when applied to the net returns data. One of the reasons this volatility was so low is that we assumed a fixed trait value which eliminated the risk associated with that parameter. The sensitivity results are shown for a range of volatilities between 5 to 30 percent in 5 percent increments. For GM, as with the salvage multiple, increasing the annualized volatility has no effect upon the breakeven acreage – another indication that salvage values would have to be extremely high in order for the option to abandon to have any effect. For GE, the increase in volatility has a negligible effect at values of 20.0 percent and higher.

SUMMARY AND IMPLICATIONS

An important evolution underway in crop breeding is the development and adoption of GM and GE technologies. These technologies have different technical processes, costs and time required for development which have important implications for trait developers and competition. GM is generally applicable for large-area crops and/or traits that can be widely adopted. As a result, GM traits have not been commercialized for crops such as wheat, barley and others which are smaller in area. In contrast, GE is thought to be lower in cost and time to develop. Further, and importantly is that for most countries, GE crops are immune from regulations over commercialization. This contrasts with GM crops which have regulations that are onerous, costly and non-harmonized across countries.

The purpose of this study is to develop a real option model that can be used to analyze the costs and risks of developing traits using either GE or GM technology. For each technology, the phase of development is discerned, and a survey was conducted of firms to elicit estimates of development costs, probability of success, and the time required at each phase of development. A real option valuation (ROV) model with an abandonment option was developed in this study to analyze differences between GE and GM in technology development. The model builds on earlier studies using real options to value investments in research, and specifically to value GM traits in crops. Real options are appropriate for two reasons. One is that there is substantial uncertainty in crop technology development, and it varies across phases of development. The other is that due to the time for development and discrete phases, developers have the option to abandon the project at any time where continuing were determined to be not attractive.

The ROV model was constructed using Microsoft Excel with the @Risk and PrecisionTree add-ins that are part of the DecisionTools Suite sold by Palisade software. @Risk incorporates Monte Carlo simulation while PrecisionTree incorporates decision tree analysis into Excel spreadsheet models.

Important features of the ROV model include combining decision trees with binomial lattices in order to apply economic valuation to the R&D and commercialization phases of new product development. Decision trees provide a better approach to modeling non-market processes such as R&D while binomial lattices are more appropriate for market-based processes such as commercialization and sales.

Many of the parameters of the model were stochastically simulated to incorporate a range of uncertainty in the parameter estimates. These parameter estimates were fed into the ROV decision tree / binomial lattice model in order to derive a distribution of ROV valuations.

The commercialization phase net returns were modeled stochastically using a linearly interpolated market penetration model where sales penetration is measured as a percentage of the maximum potential crop area that could be planted to the proposed GM or GE crop. The trait value is a user input into the model and is used to derive the net return per acre of sales for each year of commercialization.

The primary economic metric used for comparing comparable GM and GE crops (in terms of trait value and commercialization profile) was the breakeven acreage necessary for a technology firm to consider investment into R&D on the crop. This acreage is obtained by constraining the mean of the ROV valuation (prior to beginning R&D) equal to zero and solving for the maximum potential crop area parameter in the model.

The model was applied to a prototypical trait, since there are few traits that have been commercialized to date. Hence, the baseline value of the trait is assumed at $25/acre which is varied between $5/acre and $50/acre in $5 increments to incorporate a wide variety of potential values in the analysis. Both the GM and GE breakeven acreages were derived using the same trait value. A primary result from the model simulations is that, for any trait value, the breakeven acreage amount for a GE developed crop was consistently 96.3% lower than for a GM developed crop with the same trait value and commercialization profile.

Sensitivity analysis on the simulation model results indicated that GM breakeven acreage was extremely sensitive to the probability of success during the discovery phase of research and development. Increasing the probability from the baseline 5% value to 10% resulted in a 42% reduction in the breakeven acreage required. Reducing the probability from 5% to 2% resulted in a 125% increase in the breakeven acreage. GE results were slightly less sensitive to the probability of success in the discovery phase but ranged from +47% to -21% when the probability was ranged from 15% to 35% (baseline of 25%).

Both GM and GE results were less sensitive to changes in the R&D costs for discovery. These varied linearly with a marginal acreage change of 13.1 million acres for each $1.0 million change in cost for GM and a marginal change of 0.48 million acres for each $1 million change in GE discovery costs. Both sets of results showed similar sensitivity to changes in the firm's weighted average cost of capital (WACC) with the potential to reduce required acreage by 47% and 41% respectively for GM and GE when the WACC is reduced from the 15% baseline value to 10%. Likewise increases in the WACC to 20% resulted in 78% and 61% increases in GM and GE breakeven acreages.

Slightly surprising were the sensitivity results with respect to the abandonment real option parameters. Increasing the salvage value multiple from 2.0 to 4.0 (times sunk R&D costs) resulted in no change in GM breakeven acreage while GE acreage declined by 29%. One of the features of the market penetration model is a very low volatility of returns during the commercialization phase (average of 4.2 percent). Increasing the annualized volatility to 30% resulted in no change for the GM breakeven acreage while only decreasing GE acreage by 0.9%. Two observations can be derived from these results. First, for the option to abandon to become materially important, the salvage value has to be a very high percentage of the total project value when the annualized volatility factor (σ) is low (such as the case in this study). For example, our analysis indicates that with an annualized volatility of 4.2%, even if the salvage value was 100% of the NPV, the value of the option to abandon would only amount to 0.7% of the NPV. Our analysis shows that in order for the abandonment option to exceed 10% of the NPV, the annualized volatility factor would have to exceed 14.5%. Therefore, the option to abandon generally is less important in valuating projects with a low annualized volatility of cash flows.

For technology developers, there are numerous implications of these results. We identify four in particular. One relates to the economies of technology development for the two technologies. GE is substantially lower in cost and risk. Of particular importance is the lower risk in the trait discovery (D) phase of development. As a result, GE would become particularly attractive to crops and/or traits with a much lower potential acreage base. The impact of this is that technology developers can focus more on output and consumer traits. Indeed, there is already evidence of this occurring. While technology companies have in the past pursued these market segments using GM traits, they have largely failed. We are cautious here in use of the term lower-acre crops and/or traits. These results indicate that at base case values, GE technologies can be economical at 2.3 million acres. This would certainly be within the range of a number of consumer traits. However, for higher valued traits, the breakeven acres fall substantially i.e., at a $50/acre trait, the break-even acreage is 1.1 million. This makes traits, for example in the case of wheat, such as celiac, allergenicity, etc. prospectively feasible whereas they would never under GM technology.

Second is the speed of development. For a number of reasons, the speed of development using GE technologies is accelerated versus GM crops. This partly due to the impacts of regulatory requirements, but, is also due to the technology itself. Indeed, some companies (e.g., CIBUS https://www.cibus.com/our-technology.php) have suggested time to development and commercialization as short as 2-3 years; and Benson-Hill using GE, in combination with other breeding technologies (e.g., CropsOS) and data analytics, is claiming accelerated crop development. The implications if this is substantial. It means faster time to market; but, also means less risk, and cost of development. This contrasts sharply with GM technology which traditionally has been thought to require 10-15 years for development and commercialization, and exacerbated due to uncertainty in regulatory requirements.

A third implication is identification of traits. Indeed, the technology suggests there are substantial opportunities for GE due to the lower cost, risk and time to develop. However, it is not obvious what the most valuable and marketable traits are. In the case of wheat, some traits have been developed and others are being explored. However, there are far more that are potential. A major challenge for technology developers is to assess the potential traits that may have value, and then to identify genes that can be edited to meet the objective. Then, once identified, develop strategies that can be used to capture the value of the trait from customers.

Finally, an important challenge it to determine the conditions under which GM is preferred to GE. Important considerations include those related to cost, risk and time for development as discussed in this paper. In addition to these, there are important technical considerations. Some traits may only be produced using GE, or using GM. Further, the trait efficacy may be superior using GM versus GE traits. Resolution of this issue is not clear, but, certainly is a challenge for trait developers due part to the radical differences in costs, risk and time to develop.

There are also important implications for the industry. The lower cost of development for GE versus GM will no doubt induce greater entry. Indeed, the high cost and risk of GM development certainly has forestalled entry and participation in this segment, and granted some market power to incumbents. We have already seen entry of a number of de novo niche firms focusing nearly exclusively on GE development. Second, there will be an increase in differentiated (less-commoditized) crops with niche traits. This ultimately means impetuses toward pre-planting contracts with growers and/or with end-use customers. For most traits, their value would be degraded if marketed in a commodity non-segregated market. This will entail further logistical challenges to marketers. In general, for many traits their development and marketing would be facilitated more efficiently with closer relations between technology developers, germplasm providers, end-users and growers. This is already apparent with some of the new GE traits. Arcadia lists as partners many end-users, and Calyxt prescribes their traits would be/are marketed using a closed-loop supply chain.

This paper has a number of contributions. First, the economics of GE crop development require a substantially smaller market size (96.3% smaller in potential crop area) when compared to a

GM crop with the same trait value and commercialization profile. This has major implications regarding specialized crop trait development for markets considered too small for GM development (such as specialty crops, minor grains and oilseeds, consumer traits, and crops in the developing world). A second observation is that the value of the real option to abandon provides limited, if any, value to both GM and GE crop development unless the salvage value is a very high percentage of the total project value. A third observation is that the probability of success during the first (i.e., trait discovery) phase of research and development is a critical factor in determining the required potential crop area for an economically viable GM or GE crop in development.

There are a number of limitations to our analysis which can be fodder for additional studies. Most important is to determine and endogenize the value of traits into the empirical model. This is a major challenge but will be essential for further adoption and implementation of the modeling framework developed in this study.

This study only considers the real option to abandon in determining the real option value (ROV) of the GM or GE crop development project. The results indicate that the abandonment option has limited value to the project unless the salvage values are extremely high. Other types of real options (e.g., expansion, contraction, switching) may also be present and could have a more substantial and material impact upon the model results.

Finally, the model used in this study is from the perspective of evaluating a single project separate from other projects that may be present in a technology firm's portfolio. Most technology firms actually face a portfolio of potential traits which may have some correlation and risk pooling features. Further research could be done in examining the economics of GM and GE development within the context of a portfolio of potential R&D projects.

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APPENDIX A: SENSITIVITY RESULTS

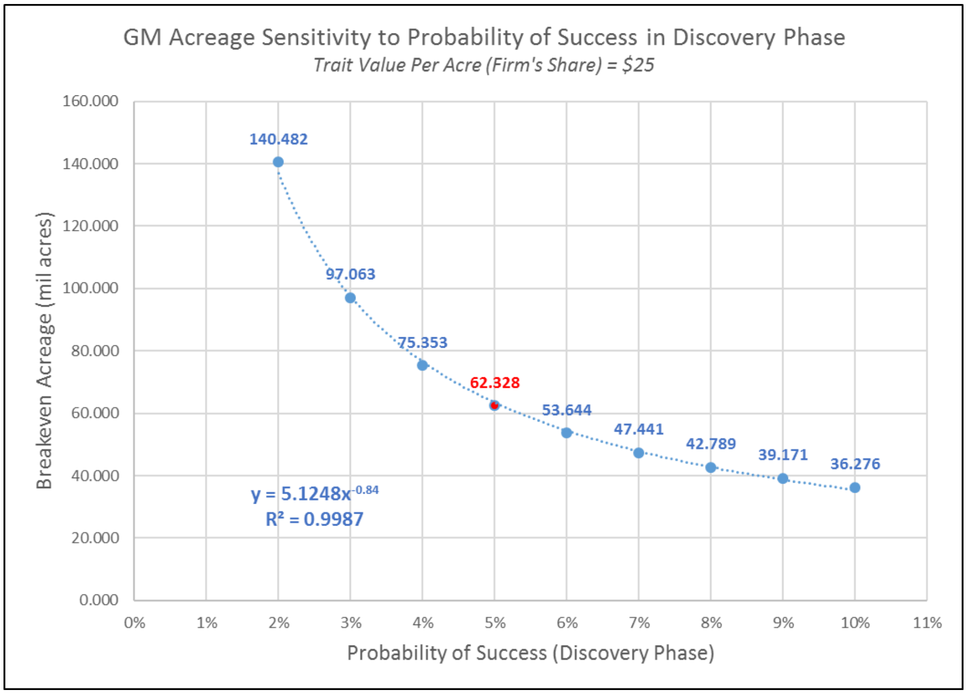

Figure A-1. GM Breakeven Acreage Sensitivity to the Probability of Success for the Discovery Research and Development Phase

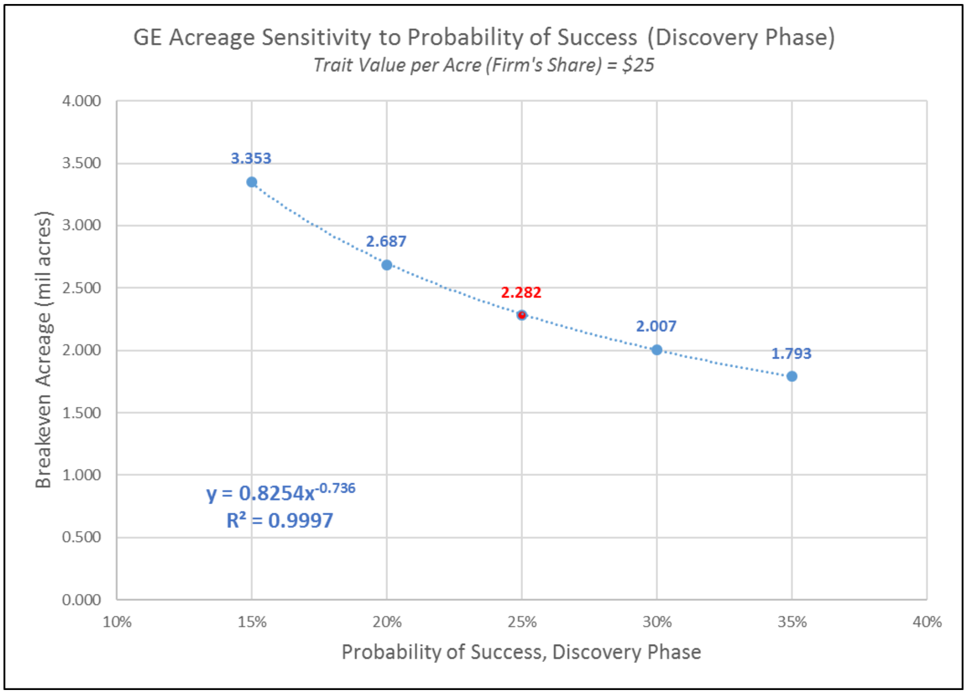

Figure A-2. GE Breakeven Acreage Sensitivity to the Probability of Success for the Discovery Research and Development Phase

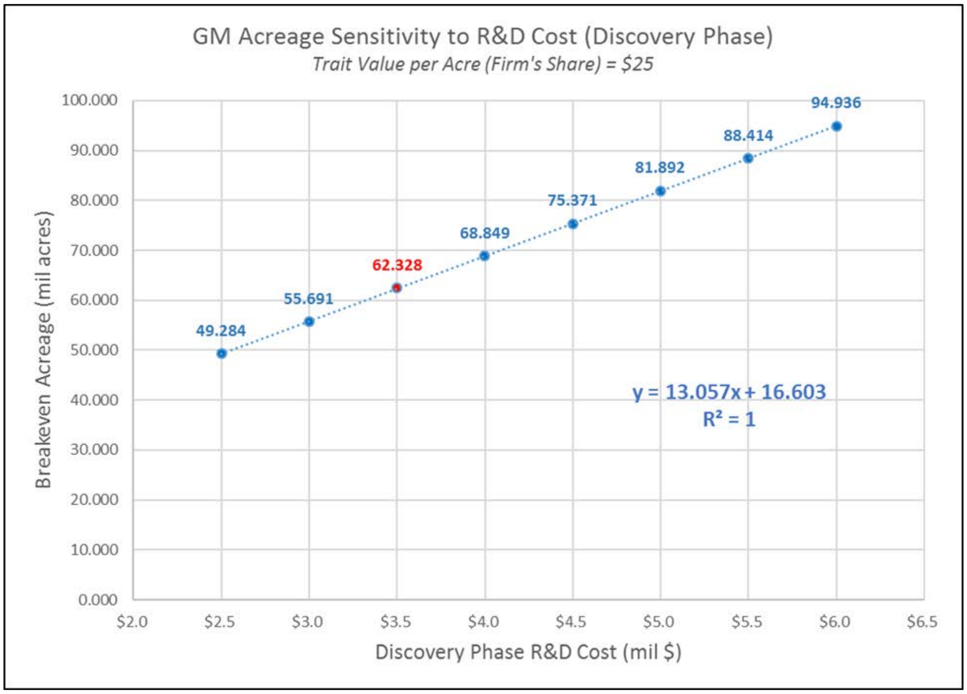

Figure A-3. GM Breakeven Acreage Sensitivity to the Mean Cost for the Discovery Research and Development Phase

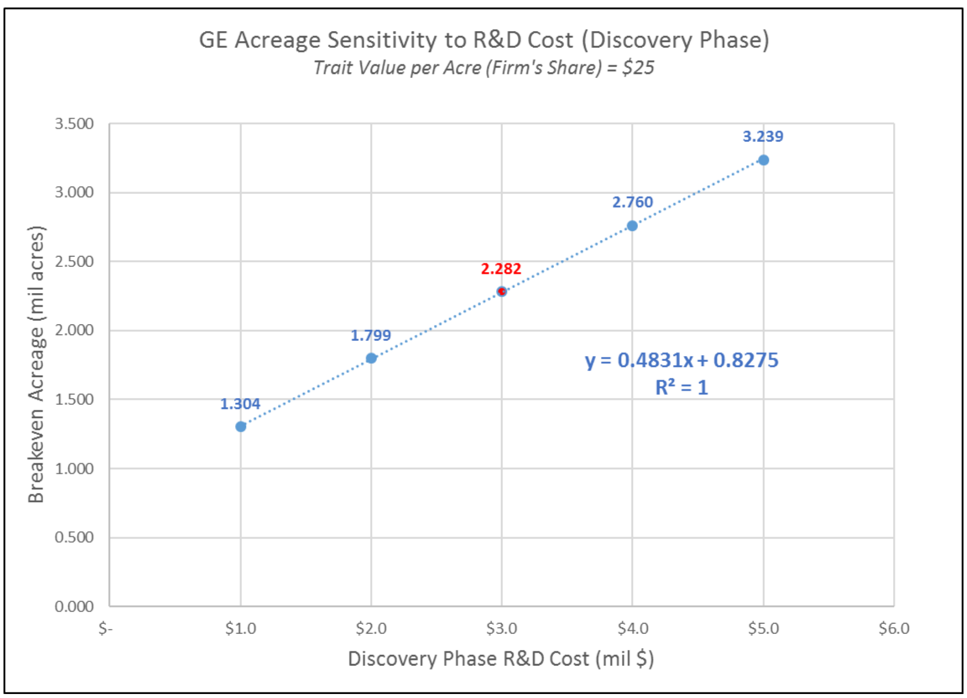

Figure A-4. GE Breakeven Acreage Sensitivity to the Mean Cost for the Discovery Research and Development Phase

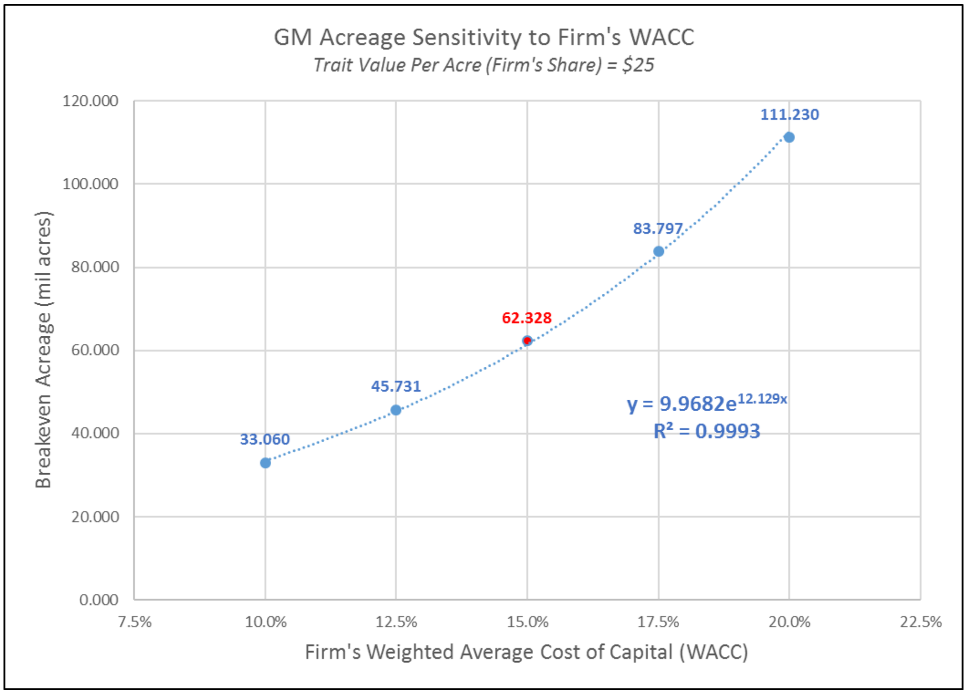

Figure A-5. GM Breakeven Acreage Sensitivity to the Research Firm's Weighted Average Cost of Capital (WACC)

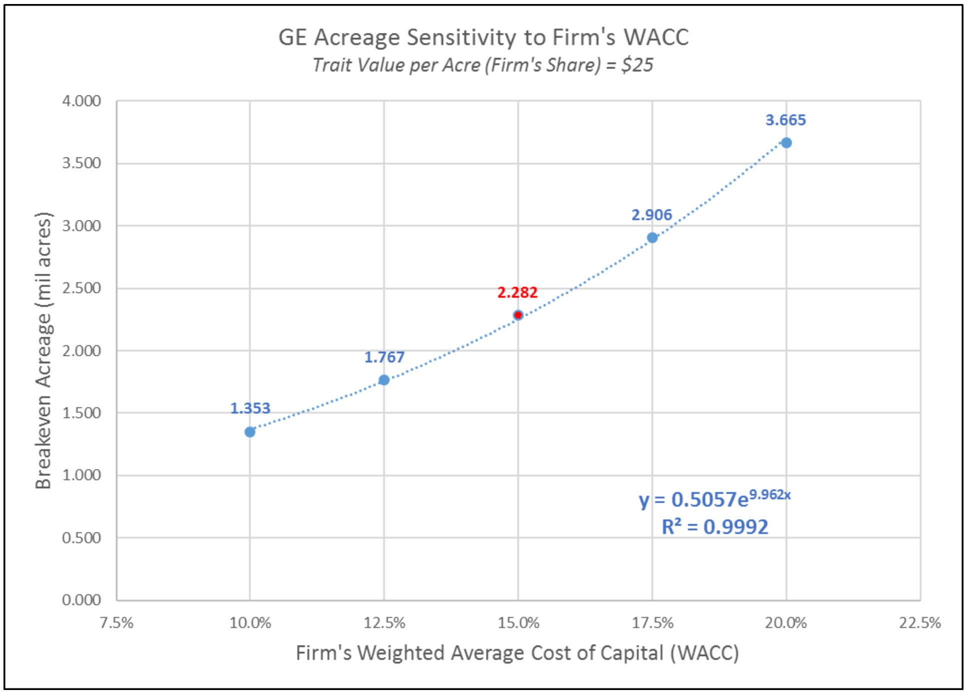

Figure A-6. GE Breakeven Acreage Sensitivity to the Research Firm's Weighted Average Cost of Capital (WACC)

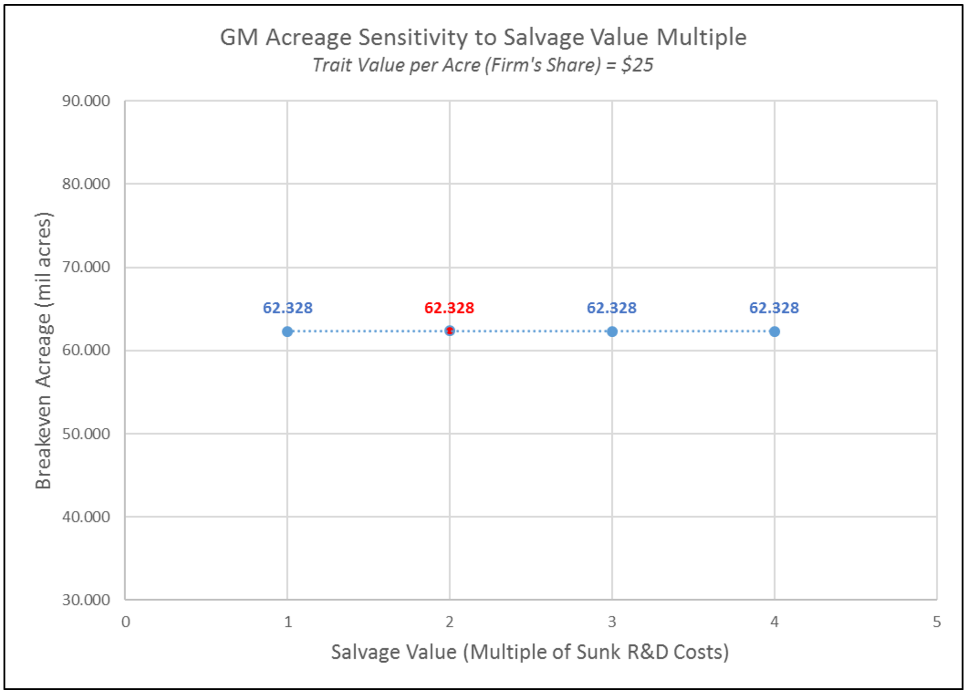

Figure A-7. GM Breakeven Acreage Sensitivity to the Salvage Value Multiple of Sunk R&D Costs

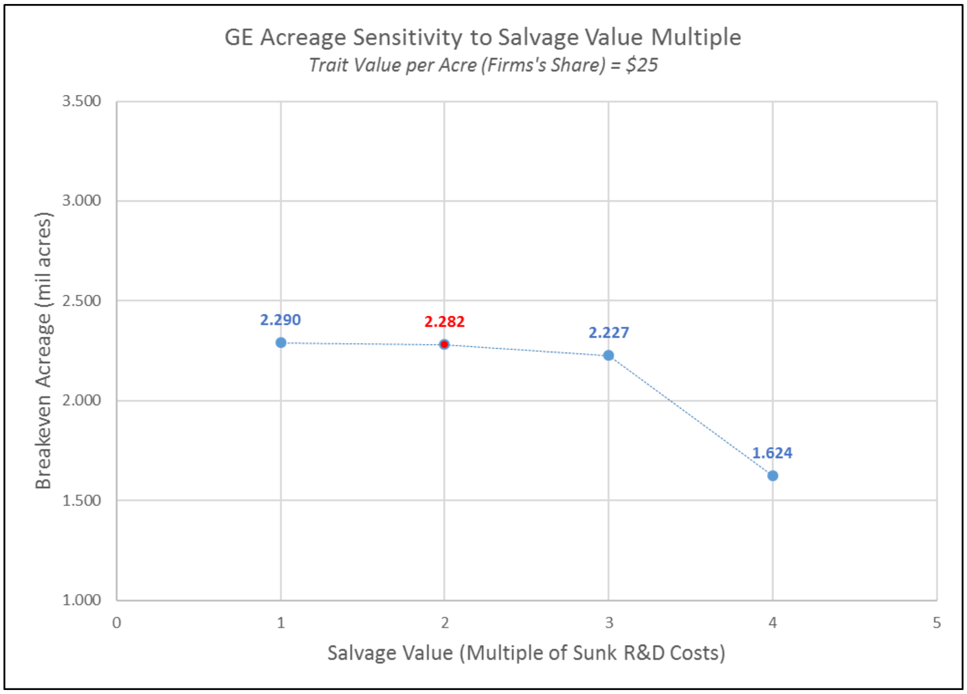

Figure A-8. GE Breakeven Acreage Sensitivity to the Salvage Value Multiple of Sunk R&D Costs

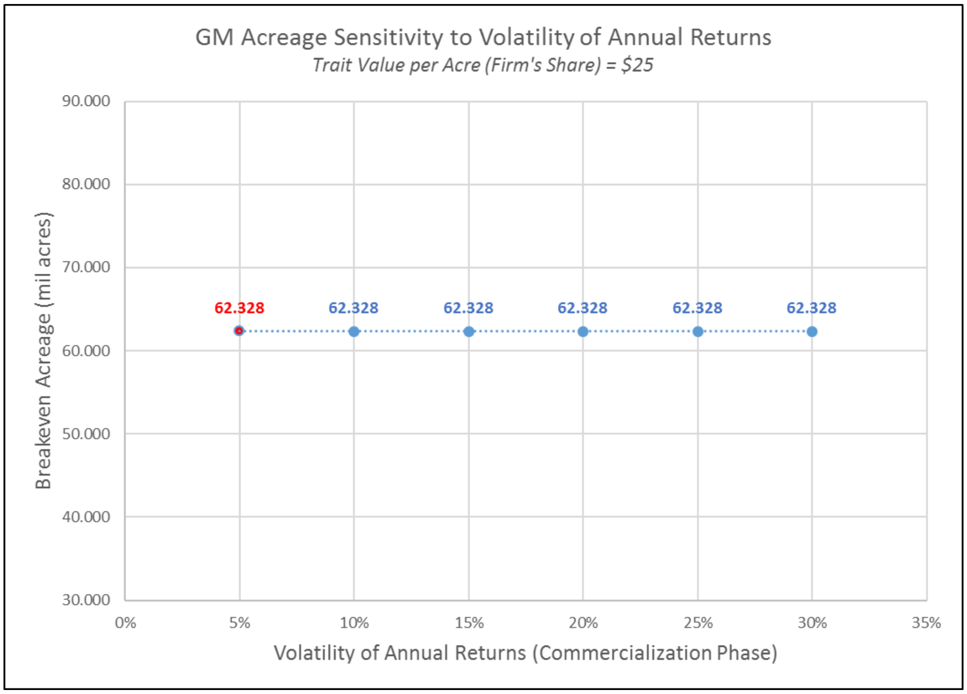

Figure A-9. GM Breakeven Acreage Sensitivity to the Annualized Volatility of Returns During Commercialization Phase

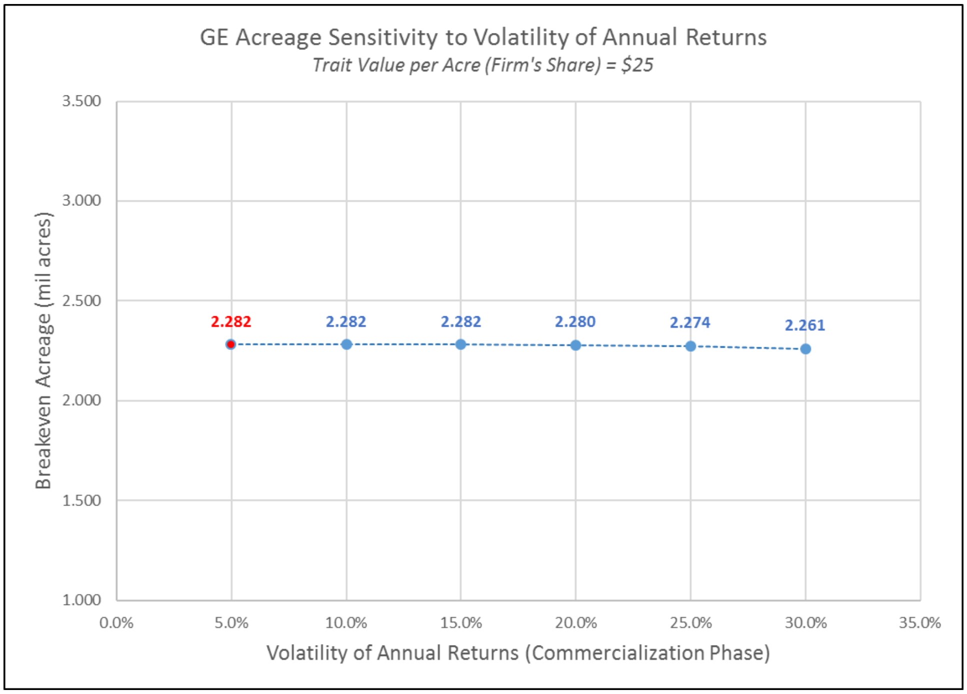

Figure A-10. GE Breakeven Acreage Sensitivity to the Annualized Volatility of Returns During Commercialization Phase