DOES CROP INSURANCE INHIBIT CLIMATE-CHANGE TECHNOLOGY ADOPTION?

by

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To my parents Bobby and Julie, my sister Rachel, and my friends

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ABSTRACT

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Changing temperatures and precipitation patterns from climate change could be a major risk to crop yields. Producers have technology options for mitigating climate change risk. One technology is Drainage Water Recycling (DWR), which involves diverting subsurface water to ponds where it is stored for later irrigation. Crop insurance could interfere with DWR by providing producers with another option to manage climate-change risk. It is hypothesized there exists a spillover effect from crop insurance, which inhibits climate-change technology adoption. The analysis investigates the DWR investment decision from a producer's viewpoint using real options analysis. The analysis considers two policy regimes: one where crop insurance is not in effect and one where crop insurance is in effect. In a Poisson jump process, it further considers the insurance effect of producer's returns jumping when facing a crop disaster. Results indicate crop insurance has a minimal effect on DWR adoption, and in many scenarios, the DWR adoption thresholds are too large for a producer to invest for climate-change mitigation. The benchmark DWR adoption scenario requires a revenue of more than double the conventional revenue of $649 per acre before a producer would consider adopting.

INTRODUCTION

Historically, U.S. Midwest agricultural production has established a balance with annual mean precipitation and water demand (Lobell et al., 2014). An example is the mitigation of any potential spring excess precipitation with artificial drainage for timely fieldwork and aeration. With climate change, the increased volatility of precipitation and its effect on crop yield may inhibit this balance. Rainfall may not consistently occur when required, leading to enhanced periods of excess precipitation accompanying summer water deficits, which may negatively affect corn and soybean yields (Lobell et al., 2014). Researchers project such variable precipitation caused by climate change to continue (Karl, 2010).

Adapting agricultural practices to climate change is a challenging process. The diversity of agricultural production creates challenges in developing broad recommendations on climate change adaptation. Climate change may be more of a threat in some regions of the U.S. compared to other areas. Climate change adaptations may not occur due to limited incentives for adoption, market failures associated with their public good nature, and limited availability of resources (McCarl et. al., 2016). There may also be reasons for producers not to adapt including practicality barriers and limits; maladaptation, where agent adaptation imposes external costs on other agents; and differential returns to adaptation as climate change progresses (Parry et. al., 2009; Barnett and O’Neill, 2010; Glantz, 1996). Another challenge is the skepticism surrounding climate change among producers. A segment of producers do not accept the scientific theory and empirical support associated with climate change and they do not observe any average yield and/or variability effects (Rejesus et. al., 2013).

In contrast, there are producers who are already taking steps to adapt their agricultural practices to climate change. Mase et. al. (2016) find in response to climate risks 64% of Midwestern U.S. corn producers are managing climate change risks by implementing in-field conservation practices, 59% are purchasing additional crop insurance, 43% are utilizing new technology, 10% are diversifying into other forms of production, and 14% are planning or considering exiting farming. Despite these challenges, there are many benefits to producers for implementing climate adaptive practices.

Technology options for mitigating climate change exist. Examples of these technologies and practices include:

Developing new crop varieties,
Developing early warning weather and climate systems,
Developing policies and programs to influence land and water resource use,
Diversifying crop and livestock types and varieties,
Changing the intensification of production,
Changing the location of crop and livestock production,
Using alternative fallow and tillage practices,
Changing the land topography,
Implementing irrigation practices, and
Changing the timing of farm operations (Smit and Skinner, 2002).

Although these options exist, producers face many hurdles in adoption. Research indicates technology investment will not occur unless sunk costs are less than the expected present value by a large hurdle rate. As an example, producers tend to wait until a random event, such as a drought, drives returns significantly above costs before investing in modern irrigation technologies (Carey and Zilberman, 2002). Such investment decisions do not exist in isolation. Schoengold et al. (2015) find producers who have had a recent catastrophic weather event such as a drought or flood are more likely to use conservation tillage.

One such technology that could potentially help mitigate the risk of increased precipitation volatility is drainage water recycling (DWR). This technology involves diverting subsurface drainage water into on-farm ponds and storing drained water for later irrigation. While implementing this technology is one possible solution to climate-change risk, there are hurdles to implementation. The sunk cost and uncertainty of the technology coupled with producer perception and alternative mitigating practices such as crop insurance all play a role in DWR adoption.

Federally subsidized crop insurance may play a role in the feasible adoption of these technologies. The insurance can have a spillover (secondary or collateral) effect on mitigating yield and revenue losses from climate change. Producers can choose between two types of crop insurance: yield or revenue protection. The coverage levels vary within the plans from 50% to 85% coverage. The subsidy decreases as the coverage level increases, so a higher coverage level results in more out-of-pocket cost for producers. Many lenders require producers to purchase federal crop insurance. The insurance reduces producers' net-return volatility, which could interfere with the market solutions to address precipitation-pattern changes such as DWR. Specifically, producers may be less likely to adopt DWR if they are able to manage their production risk through crop insurance. However, the adoption of a new technology by producers also depends on the economic and geographic feasibility of the project. The problem is government subsidized crop insurance may be interfering with DWR adoption.

The literature varies on the magnitude crop insurance interferes with the adoption of conservation practices and new agricultural technologies. Schoengold et al. (2015) indicate recent disaster and indemnity payments are associated with a decrease in the use of conservation till and an increase in the use of no-till. Smith and Goodwin (1996) find producers who purchase crop insurance tend to use fewer chemical inputs due to moral-hazard incentives. Horowitz and Lichtenberg (1993) find federally insured producers apply more nitrogen and spend more on pesticides than uninsured producers. Babcock and Hennessy (1996) find crop insurance will lead to minor reductions in applications of nitrogen if the coverage levels are at or below 70% of mean yield or revenue. There is some disagreement among the literature on the overall effect of crop insurance on agricultural inputs. Woodard et al. (2012) find crop insurance rules have incentive-distorting impacts, which disincentivize the adoption of skip-row planting, an agricultural practice that involves skipping rows when planting to better facilitate the maintenance of soil moisture. Dalton et al. (2004) find federal crop insurance programs are inefficient at reducing weather-related production risk in humid regions, and the risk management benefits from implementing a supplemental irrigation system depend on the technology and scale of the system. Without a clear consensus on the effect of crop insurance on technology adoption, a literature gap exists in determining the level of crop insurance and technology subsidies required for adoption. The question lacking an answer is the level of subsidies triggering adoption.

Implementing a DWR system is a major investment decision, which requires consideration of the interactions among investment uncertainty, irreversibility, and timing. Traditionally, investment decision-makers use expected net present value analysis (NPV) to perform feasibility analysis. This method involves summing the present value of cash inflows from making the investment and then subtracting the present value of cash outflows. If the resulting number is positive, then the firm should consider investing. The assumptions with NPV are the investment is reversible and it is possible to recover the expenditures if the firm decides to reverse their decision to invest or if the investment is irreversible, the firm will never have the option to invest again in the future (Dixit and Pindyck, 1994). Further only the first moment, expected value, is considered. Many types of new investments do not meet these criteria.

Another type of investment analysis is real options analysis. This method incorporates the option value of waiting for future information. Real options analysis factors in the interactions among uncertainty, irreversibility, and timing. The approach is appropriate to use when there is the option value of waiting for better information. Producers can delay the investment in DWR to wait for better information about climate change or they can invest today. Real options analysis also considers the irreversibility of investment decisions. The decision to invest in DWR is irreversible given the infeasibility of removing this large and complex system. Real options also stresses the ongoing uncertainty of the economic environment in which the decisions are involved. Although we can use models to predict how we think climate change will change weather patterns, there is still a lot of uncertainty with these changing weather patterns. With the weather directly influencing yields, this creates uncertainty concerning producer incomes and the economic environment of farming.

In terms of agriculture, Price and Wetzstein (1999) explore irreversible investment decisions in perennial crops with yield and price as correlated stochastic processes and Luong and Tauer (2006) consider the entry/exit conditions of coffee plantations. In forestry, numerous articles employ real options in investigating optimal rotation, investment timing, and value of timber-cutting contracts (Chaudhari et. al., 2016). For irrigation, Carey and Zilberman (2002) and Seo et. al. (2007) employ real options analysis for determining the adoption trigger and Jeuland and Whittington (2014) investigate irrigation adoption under climate change. For energy investments, real options methods consider ethanol plant investment, co-firing coal with wood pellets for electricity generation, and biodiesel investment in a disruptive tax-credit policy environment (Gonzalez et al., 2012; Stutzman et al., 2017; Liu et al., 2018). Dixit and Pindyck (1994) find significant differences between when NPV indicates to invest compared to real options analysis. NPV states the firm should invest as long as the value of the project is greater than the cost of the investment, but this is incorrect because there is an opportunity cost to investing today. Real options analysis states the firm should invest when the value of the project is at least as large as a critical value, *V**, which is greater than investment costs *I*. This critical value may be two or three times as large as *I*, which indicates the NPV rule may indicate a false positive for investment. Based on previous literature, an investigation of crop insurance impact on climate-change technology adoption requires extending the theory to consider the correlation of climate-change yield effects with and without mitigating technology along with a disruptive program, crop insurance.

The objective of this research is to measure the extent federal crop insurance interferes with DWR adoption. This study will employ a real options analysis to find the revenue thresholds which suggest investment in DWR with and without the presence of crop insurance. By comparing the two revenue thresholds, the analysis will evaluate the extent that crop insurance is interfering with DWR adoption. These revenue thresholds and intervals can be used to provide decision makers a monetary indication of the degree government mechanisms will influence DWR adoption. Results indicate only when reduction in indemnity payments from adopting DWR is close to historical highs will crop insurance spillover and negatively influence DWR adoption.

ECONOMIC THEORY

Brownian Motion

A Wiener process (also called Brownian motion) is a continuous-time stochastic process with special properties. To be a Wiener process, the variables must have three properties:

1. The variables must be a Markov process, which means the probability distribution for all future values are unaffected by past values.
2. The increments must be independent, which means the probability distribution for the change in the process over any time interval does not overlap with any other time interval.
3. Changes in the process in a finite interval of time are normally distributed.

The third property requires yield and price to be normally distributed, but this is not the case because yield or price cannot be negative. Instead, the assumption is the changes in yield and price are lognormally distributed (Dixit and Pindyck, 1994).

The equation for the Wiener process (simple Brownian motion) in continuous time is

$$dz = \epsilon_t \sqrt{dt}, \tag{1}$$

where dz is the Wiener process, ϵ_t is a normally distributed random variable with a mean of zero and a standard deviation of 1, and $\sqrt{dt}$ is the change in time. The Wiener process (simple Brownian motion) is transformable into more complex forms. One form is Brownian motion with drift, represented by the equation

$$dx = \alpha dt + \sigma dz, \tag{2}$$

where dz is the increment of a Wiener process, α is the drift parameter, and σ is the variance parameter (Dixit and Pindyck, 1994).

Further modification of the simple Brownian motion with drift represents the drift and variance coefficients as functions of the current time interval using an Ito process. An Ito process helps represent the dynamics of the variables and evolve stochastically over time and affect the decision to invest. The equation for Brownian motion with an Ito process is

$$dx = a(x,t)dt + b(x,t)dz, \tag{3}$$

where dz is the increment of a Wiener process, and $a(x,t)$ and $b(x,t)$ are nonrandom functions of the current time interval (Dixit and Pindyck, 1994).

Our model assumes price and yield are geometric Brownian motion with drift processes, which is a special case of the simple Brownian motion with drift represented by an Ito process. In (3), the nonrandom functions of the current time interval, $a(x,t,)$ and $b(x,t)$, are represented by constants where $a(x,t) = \alpha x$ and $b(x,t) = \sigma x$. The equation for geometric Brownian motion with drift is

$$dx = \alpha x dt + \sigma x dz. \qquad (4)$$

In our model, the drift represents the future change in the mean value of the price and yield. The volatility represents the future variability of price and yield (Dixit and Pindyck, 1994).

Stochastic Yield and Price

The stochastic nature of price, p, and yield, q, may be represented by geometric Brownian motion processes

$dp = \alpha_p p dt + \sigma_p p dz_p,$

$dq = \alpha_q q dt + \sigma_q q dz_q,$

where *dp* and *dq* represent the change in the per-bushel price and bushel per acre yield of corn, respectively, α is the rate of change or drift rate, σ is the standard deviation or volatility. The increment of a Wiener process is *dz*, with $E(dz_p^2) = E(dz_q^2) = dt$ and $E(dz_p dz_q) = \rho_R dt$, where ρ_R denotes the correlation coefficient between p and q. Following Price and Wetzstein (1999), letting revenue be $R = pq$, the stochastic process of revenue is then

$dR = \alpha_R R dt + \sigma_R R dz_R,$

where $\alpha_R = \alpha_p + \alpha_q + \rho_R \sigma_p \sigma_q$ and $\sigma_R = (\sigma_p^2 + \sigma_q^2 + 2\rho_R \sigma_p \sigma_q)^{1/2}$.

Let the returns in t with and without DWR be R_D and R_C, respectively. Allowing both price and yield to fluctuate randomly, two correlated geometric Brownian motion processes result

$$dR_C = \alpha_C R_C dt + \sigma_C R_C dz_C\ , \qquad (5a)$$

$$dR_D = \alpha_D R_D dt + \sigma_D R_D dz_D\ , \qquad (5b)$$

where α_C and α_D are associated with α_R, and σ_C and σ_D are associated with σ_R. The increment of a Wiener process is *dz* with the properties $E(dz_C^2) = E(dz_D^2) = dt$ and $E(dz_C dz_D) = \rho dt$, where ρ is the correlation coefficient between the uncertainty incorporated in the change of the two revenues.

The Role of Crop Insurance

DWR is not the only risk mitigating option available to the producer. Various government programs exist for a producer to avoid downside risk. One such predominant program is crop insurance. The availability of crop insurance results in producer's returns jumping when faced with a crop disaster. The effect is Poisson type policy jump on DWR adoption, investigated with the theory of investment under uncertainty. With DWR mitigating the adverse effects of weather on revenue, the expected net insurance payout, indemnity minus premium, declines with DWR adoption. Let $\theta > 0$ represent this expected decline ($\theta < 0$ an expected increase) with $\lambda_1 dt$ denoting if no current crop insurance indemnity the probability of receiving an indemnity in the next time interval, *dt.* Similarly, if receiving an indemnity currently, let $\lambda_0 dt$ represent the probability of not receiving an indemnity in the next time interval, *dt*. As assumed, producers are price takers. Following closely Dixit and Pindyck (1994) along with Lin and Huang (2010, 2011), the theory assumes a producer is considering adopting DWR with sunk cost of *I*.

It is further assumed over an interval of low returns say $(0, R_D^1)$, DWR will not be adopted regardless if there is crop insurance or not. Over the interval (R_D^1, R_D^0), DWR will be adopted if there is no crop insurance, but the producer will wait if there is crop insurance with the possibility of it being withdrawn. Beyond R_D^0 the prospect of immediate revenues will be so large, the producer will adopt DWR regardless if there is crop insurance or not. As illustrated in Figure 1, interest is in determining the threshold returns R_D^1 and R_D^0, relative to R_C, where within this revenue interval no crop insurance is effective in stimulating DWR adoption.

Interval (R_D^0, ∞): Adopt DWR

Over the range (R_D^0, ∞), the dominant strategy is to always adopt DWR regardless if there is crop insurance or not. The value of the investment opportunity is then

$$V^0(R_D - R_C) = \frac{R_D}{r-\alpha_{RD}} - \frac{R_C}{r-\alpha_{RC}} - \frac{v}{r} - I, \tag{6a}$$

in the absence of crop insurance and

$$V^1(R_D - R_C) = \frac{R_D}{r-\alpha R_D} - \frac{R_C}{r-\alpha_{RC}} - \frac{v+\theta}{r} - I, \tag{6b}$$

with crop insurance. Refer to Appendix A for the derivation of Equation (6a), where r is the discount rate, *V* and *I* are the variable and sunk costs of adopting DWR, respectively, and θ is the decline in expected net insurance payout, indemnity minus premium, from adopting DWR.

Interval (R_D^1, R_D^0): Disruptive Crop Insurance

In contrast, over the range (R_D^1, R_D^0), with no crop insurance, DWR is adopted and with it is not. Adoption without crop insurance is the same as (6a) and with, $V^1(R_D - R_C)$ is determined as follows. In the next time interval, *dt,* with crop insurance there will be a probability $\lambda_0 dt$ of no payment and DWR adopted with value $V^0[R_D - R_C + d(R_D - R_C)]$. DWR adoption will not occur with a payment, yielding a value of $V^1[R_D - R_C + d(R_D - R_C)]$. This yields

$$V^1(R_D, R_C) = e^{-rdt}\{\lambda_0 dt E V^0[R_D - R_C + d(R_D - R_C)] \\ + (1 - \lambda_0 dt) E V^1[R_D - R_C + d(R_D - R_C)]\},$$

where *E* is the expectation operator. This is the probability not receiving a payment times the value of DWR plus the probability of receiving a payment times the value of no DWR.

The Bellman equation yielding the optimal timing for DWR adoption with crop insurance (waiting to invest) is

$$E[dV^1(R_D - R_C)] = \{rV^1[R_D - R_C] - \lambda_0[V^0[R_D - R_C] - V^1[R_D - R_C]]\}dt\,, \qquad (7)$$

where over the time interval *dt* the expected rate of capital appreciation, $dV^1[R_D - R_C]$, is equal to the total expected return, the right-hand side of (7). This total expected return is the discount rate *r* times the investment value with crop insurance mitigated by the expected capital gain from not having crop insurance, the last term in (7).

Expanding the left-hand-side of (7) by employing Ito's Lemma and substituting (5) results in

$$E[dV^1[R_D - R_C]] = \alpha_{RC} R_C V_C^1 + \alpha_{RD} R_D V_D^1 + \frac{1}{2}(V_{CC}^1 \sigma_{RC}^2 R_C^2 + 2\rho V_{CD}^1 \sigma_{RC}\sigma_{RD} R_D R_C + V_{DD}^1 \sigma_{RD}^2 R_D^2)dt,$$

where $V_i^1 = \frac{\partial V^1}{\partial R_i}$ and $V_{ij}^1 = \frac{\partial^2 V^1}{\partial R_i R_j}$, i, $j = D, C$.

The Bellman equation (7) is then

$$\frac{1}{2}(V_{CC}^1 \sigma_{RC}^2 R_C^2 + 2\rho V_{CD}^1 \sigma_{RC}\sigma_{RD} R_D R_C + V_{DD}^1 \sigma_{RD}^2 R_D^2) + \alpha_{RC} R_C V_C^1 + \alpha_{RD} R_D V_D^1 - rV^1 + \lambda_0[V^0 - V^1] = 0. \qquad (8)$$

The last term captures the expected capital gain from no crop insurance. This is a partial differential equation with a free-boundary condition. As noted by Dixit and Pindyck (1994), analytical solutions are rare with numerical solutions generally only tailored for a particular problem. For this problem, a solution is possible by exploiting its homogeneity nature, which reduces it to one dimension. If the returns for DWR adoption and non-adoption are double, then the value of the investment will also double. The optimal decision then depends the ratio $\omega = \frac{R_D}{R_C}$.

This yields expression

$$V^i(R_D - R_C) = R_C f^i\left(\frac{R_D}{R_C}\right) = R_C f^i(\omega),\ i = 0,\ 1.$$

The partial differentiations are then

$$V_D^i = f_\omega^i(\omega),\ V_C^i = f(\omega) - \omega f_\omega^i(\omega),$$

$$V_{DD}^i = \frac{f_{\omega\omega}^i(\omega)}{R_C},\ V_{DC}^i = -\frac{\omega f_{\omega\omega}^i(\omega)}{R_C},$$

$$V_{CC}^i = \frac{\omega^2 f_{\omega\omega}^i(\omega)}{R_C},\ \text{i} = 0,\ 1. \tag{9}$$

Substituting (9) into (8) and rearranging

$$\frac{1}{2}(\sigma_{RC}^2 - 2\rho\sigma_{RC}\sigma_{RD} + \sigma_{RD}^2)\omega^2 f_{\omega\omega}^1(\omega) + (\delta_C - \delta_D)\omega f_\omega^1(\omega) - \delta_C f^1(\omega) + \lambda_0[f^0(\omega) - f^1(\omega)] = 0, \tag{10a}$$

where $\alpha_i = r - \delta_i$, and $f_\omega^1(\omega) = \frac{\partial f^1}{\partial \omega}$ and $f_{\omega\omega}^1(\omega) = \frac{\partial^2 f^1}{\partial \omega^2}$.

Solving (10a) yields

$$f^1(\omega) = A_1\omega^{\beta_1} + A_2\omega^{\beta_2} + \frac{\lambda_0\omega}{\delta_D(\delta_D + \lambda_0)} - \frac{\lambda_0(\frac{1}{\delta_C} + \frac{v}{rR_C} + \frac{I}{R_C})}{\delta_C + \lambda_0}, \tag{10b}$$

where A_1 and A_2 are constants and β_1 and β_2 are the positive and negative characteristic roots of the quadratic equation

$\frac{1}{2}\sigma^2 \beta(\beta - 1) + (\delta_C - \delta_D)\beta - (\delta_C + \lambda_0) = 0,$

where $\sigma^2 = \sigma_{RC}^2 - 2\rho\sigma_{RC}\sigma_{RD} + \sigma_{RD}^2$.

Interval $(0, R_D^1)$: Wait to Adopt DWR

In the final range $(0, R_D^1)$, the decision to adopt DWR is postponed regardless if there is crop insurance or not. Over this range, the differential equation for determining when to adopt DWR with crop insurance is (10a). Similarly, given no crop insurance, the differential equation for determining when to adopt DWR is

$$\frac{1}{2}(\sigma_{RC}^2 - 2\rho\sigma_{RC}\sigma_{RD} + \sigma_{RD}^2)\omega^2 f_{\omega\omega}^0(\omega) + (\delta_C - \delta_D)\omega f_\omega^0(\omega) - \delta_C f^0(\omega) + \lambda_1[f^1(\omega) - f^0(\omega)] = 0. \quad (11)$$

As demonstrated by Dixit and Pindyck (1994), (10a) and (11) yield solutions to the differential equations for the range $(0, R_D^1)$

$$f^1(\omega) = (\lambda_0\lambda_1 G\omega^{\beta_a} + \lambda_0 H\omega^{\beta_s})/(\lambda_0 + \lambda_1), \quad (12a)$$

$$f^0(\omega) = (\lambda_0\lambda_1 G\omega^{\beta_a} - \lambda_1 H\omega^{\beta_s})/(\lambda_0 + \lambda_1), \quad (12b)$$

where β_a and β_s are roots of quadratic equations (see Appendix B) with G and H parameters.

Solving the System of Equations – Value Matching and Smoothing Pasting Conditions

At the threshold R_D^1, there will be DWR adoption with no crop insurance, which leads to equality of (6a) and (12b) yielding the following value-matching and smooth-pasting conditions

$$(\lambda_0\lambda_1 G(\omega^1)^{\beta_a} - \lambda_1 H(\omega^1)^{\beta_s})/(\lambda_0 + \lambda_1) = \frac{\omega^1}{r-\alpha_{RD}} - \frac{1}{r-\alpha_{RC}} - \frac{v}{rR_C} - \frac{I}{R_C}, \text{ value matching,} \quad (13a)$$

$$(\lambda_0\lambda_1\beta_a G(\omega^1)^{\beta_a-1} - \lambda_1\beta_s H(\omega^1)^{\beta_s-1})/(\lambda_0 + \lambda_1) = 1/\delta_D, \text{ smooth pasting,} \quad (13b)$$

where $\omega^1 = R_D^1/R_C$.

For the R_D^0 threshold, the conditions are the equality of (10b) and (6b), yielding

$$A_1(\omega^0)^{\beta_1} + A_2(\omega^0)^{\beta_2} + \frac{\lambda_0\omega^0}{\delta_D(\delta_D+\lambda_0)} - \frac{\lambda_0(\frac{1}{\delta_C} + \frac{v}{rR_C} + \frac{I}{R_C})}{\delta_C+\lambda_0} = \frac{\omega^0}{r-\alpha_{RD}} - \frac{1}{r-\alpha_{RC}} - \frac{v+\theta}{rR_C} - \frac{I}{R_C}, \text{ value matching,} \quad (13c)$$

$$A_1\beta_1(\omega^0)^{\beta_1-1} + A_2\beta_2(\omega^0)^{\beta_2-1} + \frac{\lambda_0}{\delta_D(\delta_D+\lambda_0)} = 1/\delta_D, \text{ smooth pasting,} \quad (13d)$$

where $\omega^0 = R_D^0/R_C$.

Following Dixit and Pindyck (1994), the last conditions are the equality of (12a) and (10b), yielding

$$(\lambda_0\lambda_1 G(\omega^1)^{\beta_a} + \lambda_0 H(\omega^1)^{\beta_s})/(\lambda_0 + \lambda_1) = A_1(\omega^1)^{\beta_1} + A_2(\omega^1)^{\beta_2} + \frac{\lambda_0\omega^1}{\delta_D(\delta_D+\lambda_0)} - \frac{\lambda_0(\frac{1}{\delta_C} + \frac{v}{rR_C} + \frac{I}{R_C})}{\delta_C+\lambda_0}, \quad (13e)$$

$(\lambda_0\lambda_1\beta_a G(\omega^1)^{\beta_a - 1} + \lambda_0\beta_s H(\omega^1)^{\beta_s - 1})/(\lambda_0 + \lambda_1) = A_1\beta_1(\omega^1)^{\beta_1 - 1} + A_2\beta_2(\omega^1)^{\beta_2 - 1} + \frac{\lambda_0}{\delta_D(\delta_D + \lambda_0)}$.

(13f)

The six equations in (13) are solved numerically for the two thresholds, R_D^0 and R_D^1, and the four parameters A_1, A_2, G, and H.

NPV Model

Calculating the Net Present Value threshold values of the DWR investment is useful for comparison with the real options revenue thresholds. Adding the discounted value of the conventional revenue, the discounted DWR system variable cost, and the DWR sunk cost and multiplying by the difference between the discount rate and the DWR drift rate calculates the NPV of the DWR investment. The NPV ratio when crop insurance is not in effect is:

$$\omega^{NPV0} = (r - \alpha_D)\left(\frac{1}{r-\alpha_C} + \frac{V}{rR_C} + \frac{I}{R_C}\right). \tag{14}$$

The NPV formula is the same when crop insurance is in effect except the equation adds the expected net payout from crop insurance to the variable cost. The NPV ratio when crop insurance is in effect is:

$$\omega^{NPV1} = (r - \alpha_D)\left(\frac{1}{r-\alpha_C} + \frac{V+\theta}{rR_C} + \frac{I}{R_C}\right). \tag{15}$$

The NPV equations provide a revenue ratio value of the DWR investment to the conventional revenue. Multiplying by the conventional revenue results in the NPV revenue threshold. The threshold value represents the per acre level of revenue a producer requires to invest in DWR.

DATA AND METHODOLOGY

Yield and Price Data

The Variable Infiltration Capacity (VIC) model with the CropSyst crop simulation model simulate estimates for future (2041-2070) irrigated and non-irrigated west-central Indiana yield (Bowling et. al., 2018). The simulation assumes a high future greenhouse-gas concentration with a Representative Concentration Pathway of 8.5, which corresponds to the pathway with the highest greenhouse gas emissions (Riahi et. al., 2011). Figure 2 displays the non-irrigated and irrigated detrended future yield data. CropSyst also provides non-irrigated and irrigated yield data for the historic period (1984-2013). Figure 3 displays detrended historical yield data.

The source for the historical Indiana price data for the years 1984-2013 is the NASS Quick Stats website (NASS, 2018). The corn commodity PPI from the U.S. Bureau of Labor Statistics adjusts historical prices in terms of 2017 prices. Figure 4 displays adjusted historical Indiana corn prices from 1984-2013. For each year, multiplication of adjusted price and historic yield provides non-irrigated and irrigated revenues.

Unit Root Analysis

The assumption is price and yield follow a stochastic process represented by geometric Brownian motion. For determining whether or not the processes have unit roots (follow a geometric Brownian motion), consider the augmented Dickey-Fuller (ADF) test employing an AR(1) process

H_0: The data series contains a unit root.

H_a: The data series is stationary.

Model selection employs the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). Results indicate yield and price are represented by an AR(1) process. Table 1 lists the results of the ADF test applied to deflated price and detrended irrigated and non-irrigated historical and future yield. The ADF test fails to reject the null hypothesis that the data series contain a unit root for both price and yield data at even the 40% significance level.

Cost Data

A variety of scenarios are available for the cost of implementing the DWR system. The two landscape options for DWR implementation are: west-central Indiana or east-central Indiana. The west-central (east-central) landscape assumes an impounded (excavated) system. For each of these landscape options, there are three field size options: 40, 80, or 160 acres. For irrigation type, there are three options: subirrigation, big gun with traveler, and center pivot. The power source options are diesel, gas, propane, natural gas, and electric. Some assumptions made when calculating the costs of implementing the DWR systems are the drainage outlet is not limiting, there is a power source available, the earthwork costs scale up, no lift station is necessary for impoundments, and there is suitable soil on-site for construction. The design criteria for the DWR systems are a 0.5 inch drainage coefficient, an average annual drainage of 13.5 inches, a reservoir capacity of 6% of the field area multiplied by a 10 foot average depth, an 80% pumping plant efficiency, a pumping rate of six gallons per minute per acre, and a total lift of 15 feet (Reinhart and Frankenberger, 2018).

The baseline sunk and variable cost scenario in the model assumes the west-central Indiana impounded-pond system with a field size of 160 acres. The assumed irrigation type is diesel powered center pivot. The sunk cost includes the construction, land, pivot, and pumping plant. The variable cost includes the annual land cost, electricity, and labor. The total irrigated acreage of the field is 132 acres excluding the non-irrigated field corners, so per acre costs are calculated based on the total irrigated acreage (Reinhart and Frankenberger, 2018). Table 2 displays the sunk and variable costs by category.

Crop Insurance Data

Within Indiana, the most common crop-insurance policy purchased is Revenue Protection (RP), which currently accounts for 85% of the total crop insurance policies sold (RMA, 2018). In 2018, RP Indiana policies totaled more than 23,000; insuring a total of 3.75 million acres (RMA, 2018). RP insurance, first administered by the Risk Management Agency (RMA) in 2011, ensures producers receive a certain level of revenue per acre instead of a payment solely based on yield or price (Plastina and Edwards, 2014).

In Indiana, the minimum (maximum) coverage level for RP insurance is 50% (85%) of revenue, respectively (RMA, 2018). The unit structure of crop insurance determines how to group acreage. Producers can elect to insure their acres by basic, optional, or enterprise unit coverage. The basic unit structure allows for the combined insurance of owned and cash rented acres for a single crop, which combines all of the crop units. Optional separates units of a single crop by type or practice. For example, a producer may want to use an optional unit to separate owned and cash rented land or irrigated and non-irrigated land. The enterprise unit structure allows for the combination of all acres of the same crop in the same county. To qualify for enterprise units, the insured acreage must qualify for two or more basic units or two or more optional units. Figure 5 illustrates the structure of crop insurance units (Johnson, 2010; Smith, 2001). The basis for the yield calculation for RP insurance is the Actual Production History (APH) of each unit of the farm insured. To calculate an APH yield, the insurance unit must have a minimum of three years and a maximum of ten years of production history. If the minimum of three years of records are not available for the unit, RMA allows the substitution of a Transition (T) yield for the missing data. The basis for the T yield is the 10-year historical county average yield (Plastina and Edwards, 2017).

The Θ represents the decline in expected net insurance payout from adopting DWR. In calculating the value for Θ, it is necessary to understand how an Indiana producer's crop insurance policy would change if they installed an irrigation system. Contacting a licensed crop insurance agent aided in these calculations (Cole, personal communication, August 31, 2018). The agent indicated with the adoption of DWR, producers would generally switch their RP insurance units from enterprise to enterprise by practice. This would allow the separation of irrigated and non-irrigated fields.

The U.S. Bureau of Land Management divides property using the Public Land Survey System (PLSS). The typical division of each county is into 16 townships and the division of townships is into 36 sections. To qualify for enterprise by practice, a producer must have at least 20% of the insured crop acreage in this practice in a separate section. As an example, a producer would not qualify for enterprise by practice if they only have one irrigated field. They would require at least one other irrigated field in a separate section from the irrigated field, which is greater than, or equal to 20% of the producer's insured crop acreage in the enterprise unit. In addition, if a producer switches to enterprise by practice, they are required to move their insurance coverage on irrigated acres down a minimum of one level. For example, if a producer has 85% coverage RP insurance in enterprise units and wants to switch to enterprise by practice units, they are required to move down to 80% coverage on the irrigated acres (Cole, personal communication, August 31, 2018).

Despite the separation of irrigated fields for RP insurance, the magnitude and direction of the expected net crop insurance payout from adopting DWR is ambiguous. The expected net insurance payout may increase or decline depending on the change in premium and expected indemnity. If producers switch from enterprise to enterprise by practice, their premiums will decrease given the imposed step down in coverage level. However, by how much the premium will decline is ambiguous given dependence on the initial coverage and the actual change in coverage level following the implementation of DWR. Also, not all producers may start out in enterprise units. With basic or optional units, a move to enterprise by practice would also realize a reduction in premiums from higher premium subsidies associated with enterprise units relative to basic or optional units. A move from basic or optional units to enterprise units would also affect revenue guarantees and thus expected indemnities. In addition, the reduced yield risk and increased APH associated with DWR influence expected indemnity reduction. However, a necessary lag in realizing these benefits would result from the requirement to build up a minimum of three years APH. During this lag, the change in expected indemnity would depend on the productivity of the farm relative to the average productivity of county irrigated acreage. If the farm is more productive than the average county irrigated acreage, this would decrease the farm's APH and increase the expected indemnity. If the farm is less productive than the average county irrigated acreage, this would increase the farm's APH and reduce the expected indemnity. If the decline in premium the producer pays is greater (less) than any possible gain in the expected indemnity, then the direction is negative (positive). The specific value of Θ is indeterminate and influenced by the net change in premiums and indemnity. For analysis, a baseline value of $\Theta = 0$ is set with a range based on RMA crop insurance data.

For determining the range of Θ, the RMA Summary of Business Reports by State/County/Crop/Coverage Level from 2011-2017 is used. Only seven years of data exists, given the establishment of RP in 2011. For Indiana, the data contain total premium, subsidy, and indemnity payment by coverage level for RP insurance. The division of the annual premium, total premium, subsidy, and indemnity by the number of acres insured determines the associated mean per acre. Subtracting the per-acre premium from the indemnity calculates the total annual payout received per acre. Calculations determine the total payout per acre for each coverage level from 2011 to 2017. The overall average across all the years is then determined for each coverage level, which yields the total average per-acre payout. The listing of averages for each coverage level is in Table 3. The average total payout per acre ranges from $19.99 to $52.58 for a 50% and 70% coverage level, respectively. This indicates a change in the net insurance payout is likely to be within a range similar to the average net payout.

Another scenario for calculating the range of Θ is if crop insurance were not subsidized. Subtracting the total premium per acre, which excludes the subsidy, from the indemnity per acre yields a range of values for each coverage level. This yields the total non-subsidized payout per acre for each coverage level from 2011 to 2017. The average for all coverage levels is then calculated and represented in Table 3. This yields a range from $4.97 to $26.07 for a 55% and 85% coverage level, respectively. These values are less than the values with a subsidy given producers are responsible for a larger portion of the premium, which yields lower net returns. The change in the net insurance payout is assumed to be within a range similar to the absolute net payout without premium subsidies, or ±$30. For analysis, the range of Θ is set from −$30 to +$30 for determining the impact of changes in crop insurance on the decision to invest in DWR.

The limitation of using the RMA business summary data is the limited number of years available. Given changes in crop insurance policy, the current version of RP crop insurance utilized by the majority of Indiana producers started in 2011, and thus only seven years of data exists. Further complicating the data issue, the small sample of years employed to evaluate net returns includes 2012, a year characterized by severe drought (Rippey, 2015). This resulted in large crop insurance indemnity payments. Coupled with the small number of sample years, this likely results in larger positive expected net insurance payouts than expected in the long run. In the long run, actuarially fair crop insurance would result in average net payout without premium subsidies approximately zero (Yu and Sumner, 2018). This would result in Table 3 values closer to zero. Similarly, the expectation is average net payouts with premium subsidies equals the value of the subsidy in the long run.

Estimation Procedure

Table 4 displays the benchmark parameter values and parameter ranges for the sensitivity analysis. Follwing Dixit and Pindyck (1994) and supported by the ADF test, price and yield follow geometric Brownian motion with their logarithms follow a simple Brownian motion

$$d(lnx) = \left(\alpha - \frac{1}{2}\sigma^2\right) dt + \sigma dz.$$

where $d(lnx)$ follows a normal distribution with mean μdt and variance $\sigma^2 dt$ over a finite time interval t. Absolute changes in x, Δx, are lognormally distributed.

For the first difference of the logarithm of historical prices, non-irrigated and irrigated future yield, the drift (μ) and volatility (σ) are estimated by applying the maximum likelihood method to the simple Brownian motion

$$\hat{\mu} = \bar{\gamma} = \frac{1}{n}\sum_{t=1}^{n} \gamma_t,$$

$$\hat{\sigma} = std\ (\gamma_t) = \sqrt{\frac{1}{n}\sum_{t=1}^{n} (\gamma_t - \hat{\mu})^2}\ .$$

where *n* is the number of observations and $\gamma_t = \Delta x_t \ / \ x_t$. The estimate for drift is:

$$\hat{\alpha} = \hat{\mu} + \frac{1}{2}\hat{\sigma}^2.$$

These formulas are used to estimate price drift, α_p, price volatility, σ_p, conventional yield drift, α_C, conventional yield volatility, σ_C, DWR yield drift, α_D, and DWR yield volatility, σ_D.

The conventional revenue drift, α_{RC}, and volatility, σ_{RC}, are

$$\alpha_{RC} = \alpha_p + \alpha_C + \rho_C \sigma_C \sigma_p,$$

$$\sigma_{RC} = \sqrt{{\sigma_p}^2 + {\sigma_C}^2 + 2\rho_C \sigma_p \sigma_C}\ .$$

Similarly, DWR revenue drift, α_{RD}, and volatility, σ_{RD}, are

$$\alpha_{RD} = \alpha_p + \alpha_D + \rho_D \sigma_D \sigma_p,$$

$$\sigma_{RD} = \sqrt{{\sigma_p}^2 + {\sigma_D}^2 + 2\rho_D \sigma_p \sigma_D}\ .$$

Parameters ρ_C and ρ_D are the correlation between price and historical conventional and irrigated yield, respectively.

Overall revenue volatility is

$$\sigma_R = \sigma_{RC}^2 - 2\rho_R \sigma_{RC} \sigma_{RD} + \sigma_{RD}^2.$$

where ρ_R denotes the correlation coefficient between DWR and conventional revenue]

The model assumes a risk-free interest rate, r of 5%. If the producer receives a crop insurance indemnity in this time interval, the model assumes the probability the producer receives an indemnity in the next time interval, λ_0 is low. If the producer does not receive a crop insurance indemnity in this time interval, the model assumes the probability of an indemnity in the next time interval, λ_1 is also low. The benchmark change in expected net insurance payout from adopting DWR, θ, is zero and sensitivity analysis is performed on this parameter. Multiplying 2017 yield and price results in a value for conventional revenue, R_C. The difference between the expected rate of return and the expected capital gain with no DWR, δ_C, is $\delta_C = r - \alpha_{RC}$, and the difference between the expected rate of return and the expected capital gain with DWR (δ_D) is $\delta_D = r - \alpha_{RD}$. Table 5 lists the benchmark values and parameter ranges for the NPV model.

RESULTS AND DISCUSSION

Benchmark Results

Populating the models with the benchmark parameters produce the revenue ratios and revenue thresholds with and without crop insurance. Setting the benchmark value for the change in expected net insurance payout from adopting DWR, θ, to zero results in equivalent revenue ratios when crop insurance is in effect and not. The revenue ratios are multiplied by the conventional revenue, R_C, to calculate the revenue thresholds. The revenue threshold means if revenue reaches the per-acre threshold value, producers should consider adopting the DWR technology as a way to mitigate the risk associated with climate change. Table 6 lists the benchmark real options and NPV under crop insurance distortion scenarios where $\theta = \pm\$30$. Figures 6 through 8 illustrate the revenue thresholds under the different real options and NPV analysis scenarios.

Employing NPV indicates investing much sooner than real options analysis. The difference between NPV analysis and real options analysis has major implications for policy makers. If policy makers focus on the NPV analysis results, then a much smaller policy incentive is required to trigger DWR adoption compared to the more robust real options model.

With zero net change in insurance payout, crop insurance will have no effect on either real options or NPV (Table 6 and Figure 6). The revenue threshold considering real options is markedly higher, \$1358, than the NPV threshold, \$810. The real options revenue threshold is 109% higher than the conventional revenue of \$649. Revenue has to be 68% higher for adoption under the real options criterion compared with NPV. The ability to wait has value given the cost of investment decreases by a larger discount factor than the revenue it generates. This value of waiting option is also associated with the stochastic nature of adoption. Revenue may fall in subsequent periods after adoption, which discourages adoption. There is a value to waiting, option value, which once the option is exercised it is lost. The results indicate this option value for DWR adoption is \$548 (1358 – 810).

Considering the effect of crop insurance does not have much of an impact on the adoption thresholds (Table 6 and Figure 7). In the extreme, a net decrease in insurance payout from adoption of DWR of \$30 only increases the adoption thresholds for real options and NPV by

2.02% (1361/1334) and 1.48% (822/810), respectively. The low change in net insurance payout from DWR adoption does not result in much, if any, increase in the revenue thresholds. Crop insurance does not appear to influence the adoption of DWR. This maybe the result of crop insurance and DWR addressing different types of risk. DWR addresses yield loss from inadequate moisture by reducing crop-moisture stress between rainfall events. This yield enhancement positively effects yields. In contrast, crop insurance, as designed, covers catastrophic weather events including major droughts within a growing season. In the current time interval, catastrophic weather events do not occur every year and a producer does not continually receive a large payout in crop insurance over an extend period of time. Crop insurance has little influence on the economics on efforts to enhance yields through relieving crop stress between periods of rainfall. There appears to be limited if any crowding out of DWR by crop insurance. In general, results indicate crop insurance as a program for addressing catastrophic weather events is not inhibiting adoption of technology for addressing negative agricultural weather effects from climate change.

Table 7 compares the real options revenue thresholds, NPV revenue thresholds, and conventional revenue. The real options revenue thresholds range from \$524 to \$572 per acre above the NPV thresholds, which is equal to 65% to 71% higher than the NPV thresholds. Real options suggests waiting to invest in DWR until revenue is much higher than the NPV value. NPV fails to account for the uncertainty in waiting for better information and uncertainty in crop insurance policy. The real options revenue threshold values are also significantly higher than the current conventional revenue of \$649 per acre. The real options revenue thresholds range from \$685 to \$733 per acre above conventional revenue, which is 106% to 113% higher than conventional revenue. When analyzing the DWR investment decision using real options analysis, conventional revenue would have to more than double before DWR adoption would be close to being feasible.

Sensitivity Analysis

Sensitivity analysis on the real options parameters (Table 4) and on the NPV parameters (Table 5) creates a deeper understanding of the results. Figure 9 illustrates the response of revenue thresholds to the change in θ, the expected net crop insurance payout from adopting DWR. As the change in expected net insurance payout increases, θ, the threshold when crop insurance is not in effect, R_D^1, decreases and the threshold when crop insurance is in effect, R_D^0, slightly increases. When crop insurance is not in effect, a positive net change in expected crop insurance payout positively affects DWR adoption, and a negative expected crop insurance payout negatively affects DWR adoption. However, the change in the revenue thresholds as θ increases from -30 to 30 is relatively small. The revenue threshold when crop insurance is not in effect ranges from \$1382 per acre when $\theta = -30$ to \$1334 per acre when θ =30. In total, the revenue threshold changes by \$48 per acre. The revenue threshold when crop insurance is in effect ranges from \$1355 per acre when $\theta = -30$ to \$1316 per acre when θ =30. In total, the revenue threshold changes by \$39 per acre.

The slope of the line when crop insurance is not in effect is approximately -0.80 and the slope of the line when crop insurance is in effect is approximately 0.10. The larger slope when crop insurance is not in effect indicates the revenue threshold is more responsive to a change in the net crop insurance payout when crop insurance is not in effect, than when crop insurance is in effect. The elasticity of the net change in expected crop insurance payout when crop insurance is not in effect is and the net change in crop insurance payout is \$30 per acre is -0.028. If the net change in expected crop insurance payout decreases by 1%, the revenue threshold increases by 0.028%. The elasticity of the net change in expected crop insurance payout when crop insurance is in effect and the net change in crop insurance payout is \$30 per acre is 0.220, highly inelastic. If the net change in expected crop insurance payout decreases by 1%, the revenue threshold decreases by 1%. The revenue thresholds are not very responsive to a change in the expected net crop insurance payout when crop insurance is and is not in effect. The implication of the sensitivity analysis of the net expected change in crop insurance payout for the producer making the decision today is they are not likely to invest due to the high adoption costs of DWR in an environment where crop insurance exists and when crop insurance does not exist.

Figure 10 represents the response of the revenue thresholds to the variable cost of adopting DWR and Figure 11 represents the response to the sunk cost of adopting DWR. The response thresholds are similar as sunk and variable costs have positive linear effects on the revenue thresholds. The larger the sunk and variable costs, the greater the revenue thresholds for DWR adoption. For the producer considering the DWR investment decision, all DWR sunk and variable cost scenarios are too large to consider investment in DWR. Even at the lowest sunk and variable cost sensitivity scenarios, the revenue threshold is more than double the conventional revenue.

The variable cost elasticity at the benchmark value is 0.019, highly inelastic. If the variable cost of DWR decreases by 1%, then the revenue threshold decreases by 0.019%. Decreasing the variable cost of DWR adoption will only cause a small decrease in the revenue threshold. The sunk cost elasticity at the benchmark value is 0.165, highly inelastic. If the sunk cost of DWR decreases by 1%, then the revenue threshold decreases by 0.165%. A large decrease in the sunk cost will only cause a small decrease in the revenue threshold. The implication of the sunk and variable cost elasticity is any type of subsidy of the DWR system will not be very effective as a decrease in cost will not reduce the revenue threshold very much. A policy subsidizing DWR adoption would be ineffective considering the benchmark DWR adoption scenario.

Figure 12 illustrates the response of the revenue threshold to the conventional revenue drift rate. The benchmark value for the conventional revenue drift rate is calculated using detrended yield data, so there is no upward trend in the yield assumed. Because the benchmark value assumes no upward trend in conventional yield, it is important to perform sensitivity analysis on the conventional revenue drift rate. An increase in yield from technical change is likely to drive any future change in the revenue drift. Varying the conventional revenue drift rate allows for the exploration of the response when there is upward trend in conventional yield. The thresholds increase at an increasing rate as the conventional revenue drift rate increases. The greater the expected increase in conventional yield and price in the future, the higher the conventional revenue drift and the less valuable the DWR investment becomes, so producers would delay investment in DWR as a method to mitigate climate change risk.

Figure 13 illustrates the response of the revenue threshold to the DWR revenue drift. As the DWR revenue drift increases, the revenue thresholds decrease. The greater the expected future increase in DWR yield and price, the higher the DWR revenue drift. This results in the DWR investment becoming more valuable to adopt, so the revenue thresholds decline. The DWR yield is most likely to drive the increase in DWR revenue drift, as price drift has mostly remained steady over time. New technology, improved crop genetics, or yield response to the irrigation system if climate change become more severe could cause the DWR yield to increase.

Figure 14 illustrates the response of the revenue thresholds to the conventional revenue volatility for the real options model. The thresholds decrease and then increase at an increasing rate after the conventional revenue volatility value of 0.22. To understand why the thresholds yield this U-shape, it is important to understand the effect of the conventional revenue volatility on the overall revenue volatility. The formula for overall revenue volatility is:

$$\sigma_R = \sigma_{RC}^2 - 2\rho_R\sigma_{RC}\sigma_{RD} + \sigma_{RD}^2$$

The derivative in the overall revenue volatility with respect to the conventional revenue volatility is:

$$\frac{\partial\sigma_R^2}{\partial\sigma_{RC}} = 2\sigma_{RC} - 2\rho_R\sigma_{RD},$$

which results in $\sigma_{RC} = \rho_R\sigma_{RD}$. The benchmark value for $\rho_R\sigma_{RD} = 0.22$. This results in the following:

$$\frac{\partial\sigma_R^2}{\partial\sigma_{RC}} > 0 \; if \; \sigma_{RC} > 0.22,$$

$$\frac{\partial\sigma_R^2}{\partial\sigma_{RC}} < 0 \; if \; \sigma_{RC} < 0.22.$$

Figure 15 illustrates the response of the revenue thresholds to the DWR revenue volatility. The thresholds first decline and then increase at an increasing rate after the value of 0.22. Similar to the conventional revenue volatility, the DWR revenue volatility affects the overall revenue volatility calculation. The derivative in the overall revenue volatility with respect to the DWR revenue volatility is:

$$\frac{\partial\sigma_R^2}{\partial\sigma_{RD}} = -2\rho_R\sigma_{RC} + 2\sigma_{RD},$$

which results in $\sigma_{RD} = \rho_R\sigma_{RC}$. The benchmark value for $\rho_R\sigma_{RC} = 0.22$. This results in the following:

$$\frac{\partial\sigma_R^2}{\partial\sigma_{RD}} > 0 \; if \; \sigma_{RD} > 0.22,$$

$$\frac{\partial\sigma_R^2}{\partial\sigma_{RD}} < 0 \; if \; \sigma_{RD} < 0.22.$$

As the conventional and DWR revenue volatilities grow farther apart, the revenue threshold increases. For the producer making the DWR adoption decision, it is best to invest when the volatilities are similar. If the volatilities both decrease and are similar, this decreases the revenue threshold so a producer would be more favorable toward investment when the DWR and conventional revenue volatilities are low.

Figure 16 illustrates the response of the revenue thresholds to the correlation coefficient between the uncertainty incorporated in the change of the two revenues. The thresholds are decreasing at an increasing rate as the correlation coefficient increases. As the correlation coefficient increases, the overall revenue volatility, σ_R, decreases. As σ_R decreases, the characteristic root associated with the quadratic, β_1 ,for the range (R_D^0, R_D^1), increases and $\frac{\beta_1}{(\beta_1 - 1)}$ decreases. The smaller the amount of uncertainty over the future values of the DWR investment, the smaller the excess return the producer will demand before they are willing to invest in DWR (Dixit and Pindyck, 1994). When considering the producer who is making the DWR adoption decision, if DWR revenue and conventional revenue are highly correlated, the producer will invest sooner because there is less uncertainty and the producer will require less excess revenue to invest in DWR. If the correlation between DWR revenue and conventional revenue is low, the producer faces more uncertainty so they will require more revenue to invest in DWR. The producer may instead consider investing in other climate change adaption strategies, which have less uncertainty.

Figure 17 illustrates the response of the revenue thresholds to the discount rate. The thresholds are decreasing at a decreasing rate until the discount rate reaches 5.8% and then the thresholds increase at an increasing rate. After 5.8%, there is a negative relationship between the interest rate and the revenue threshold where an increase in the interest rate increases the revenue threshold required to adopt DWR. The value of the DWR investment opportunity is:

$$V^0(R_D - R_C) = \frac{R_D}{r - \alpha_{RD}} - \frac{R_C}{r - \alpha_{RC}} - \frac{V}{r} - I.$$

Subtracting the discounted value of the conventional revenue, the discounted variable cost, and the sunk cost from the discounted value of the DWR revenue results in the value of the investment. As the discount rate increases, the difference between the DWR revenue and the conventional revenue declines so the revenue thresholds increase. Multiplying the equation by R_C results in:

$$V^0(R_D - R_C) = \frac{\omega}{r - \alpha_{RD}} - \frac{1}{r - \alpha_{RC}} - \frac{V}{rRc} - \frac{I}{R_C},$$

where $\omega = \frac{R_D}{R_C}$. When $r < 5.8\%$, the ratio of variable cost the conventional revenue multiplied by the discount rate, $\frac{V}{rR_C}$, is greater than 1, which causes the revenue thresholds to decrease. When $r > 5.8\%$, the ratio of variable cost the conventional revenue multiplied by the discount rate, $\frac{V}{rR_C}$, is less than 1, which causes the revenue thresholds to increase. Two factors make up the discount rate: time value of money and uncertainty risk. As the discount rate increases, the producer's time value of money and uncertainty risk increase. The increase of these factors makes DWR less attractive as an investment for the producer and the revenue thresholds increase.

Probability of Indemnity Payment

When the change in expected net crop insurance payout is positive (negative), crop insurance and DWR adoption are substitutes (complements). A Poisson process represents two regimes: one where crop insurance is in effect and one where crop insurance is not in effect. The probabilities of a producer receiving a crop insurance indemnity are described by Poisson variables λ_0 and λ_1. The probability of receiving an indemnity in the next time interval if no indemnity occurs in this time interval is λ_1 and the probability of not receiving an indemnity in the next time interval if an indemnity occurs in this time interval is λ_0 .

Table 8 and Figure 18 display the revenue thresholds in a state where crop insurance is not in effect and the net change in the expected crop insurance payout is \$30. The revenue thresholds for DWR adoption increase as the probability of receiving an indemnity in the next time interval increases. As the probability of not receiving an indemnity in the next time interval increases, the revenue thresholds decrease.

Table 9 and Figure 19 display the revenue thresholds in a state where crop insurance is in effect and the net change in the expected crop insurance payout is \$30. The revenue thresholds for DWR adoption increase as the probability receiving an indemnity in the next time interval increases and decrease as the probability of not receiving an indemnity in the next time interval increases.

Table 10 and Figure 20 display the revenue thresholds in a state where crop insurance is not in effect and the net change in the expected crop insurance payout is $-$\$30. The revenue thresholds for DWR adoption decrease as the probability of receiving an indemnity in the next time interval increases. As the probability of not receiving an indemnity in the next time interval increases, the revenue thresholds increase.

Table 11 and Figure 21 display the revenue thresholds in a state where crop insurance is in effect and the net change in the expected crop insurance payout is −$30. The revenue thresholds increase as the probability of not receiving an indemnity in the next time interval increases and decrease as the probability of receiving an indemnity in the next time interval increases.

DWR Subsidy

One reason policy makers may consider subsidizing DWR is the internalization of the negative externalities (positive social benefits). The nutrient runoff from farms into the water supply is a negative externality of agricultural production. Subsidizing DWR, which reduces nutrient runoff into water systems, has positive social benefits. If the sunk cost of the DWR system is completely subsidized, $I = 0$, the NPV revenue threshold is $676 per acre and the real options revenue threshold is $1,133 per acre. The NPV revenue threshold is close to the conventional revenue of $649 per acre, which means producers may now consider adopting DWR. The real options revenue threshold is 75% higher than the conventional revenue, indicating producers are not likely to currently consider investing in DWR even if the sunk cost is completely subsidized. One reason the DWR system is still too expensive when subsidized in the benchmark scenario is the variable cost is greater than any expected yield gains from the irrigation system. The DWR yield drift and volatility are very close to the conventional yield drift and volatility in the benchmark scenario. If the DWR yield volatility decreases and the DWR yield drift increases compared to the conventional yield, this would be beneficial for the feasibility of the DWR investment. Real options analysis suggests delaying the adoption decision until the next time interval to observe what happens to revenue. If the climate change widens the drift and volatility between conventional and irrigated yields, then the DWR investment decision may be more valuable in the next time interval and the producer may consider adopting.

Monte Carlo Analysis

Monte Carlo analysis explores the sensitivity of the revenue threshold with and without crop insurance for the real options and NPV model. For the analysis, a Monte Carlo simulation generates 5000 random draws of the parameters using the uniform distribution over the ranges listed in the Tables 4 and 5. Table 12 lists the probability of the revenue threshold with crop insurance and without crop insurance being below specific thresholds for the real options model. Table 13 lists the probability of the revenue threshold with crop insurance and without crop insurance being below specific thresholds for the NPV model. Figure 23 illustrates the CDF for the real options and NPV revenue thresholds with and without crop insurance. The NPV with crop insurance and NPV without crop insurance follow the same distribution, so the line is the same for both in the figure. The NPV distribution is more left-skewed than the real options distribution. For the real options Monte Carlo, less than ½% the revenue thresholds without and with crop insurance are below the conventional revenue \$649.00 per acre. This is in contrast to the NPV Monte Carlo with more than 10% of the revenue thresholds below the conventional revenue.

Feasible DWR Adoption Scenarios

Although the benchmark real options model scenario is infeasible, there are scenarios where DWR adoption could be feasible. Table 14 lists the parameter values for a scenario where DWR adoption is feasible. The revenue thresholds are \$639 per acre when crop insurance is not in effect and \$735 per acre when crop insurance is in effect, so the producer would adopt when crop insurance is not in effect because the revenue threshold is lower than conventional revenue of \$649 per acre, and wait to adopt when crop insurance is in effect. This scenario demonstrates if climate change causes conventional yield to decrease, DWR yield to increase, and if the sunk cost of DWR is completely subsidized then DWR adoption could become feasible for the producer.

Applying the same scenario to the NPV DWR adoption model results in a feasible NPV adoption scenario. Table 15 displays the parameter values for the NPV model. The revenue threshold for NPV DWR adoption are \$11.61 per acre when crop insurance is not in effect and \$12.18 when crop insurance is in effect. NPV suggests investing in DWR when crop insurance is and is not in effect. The revenue threshold for NPV adoption are much lower in the feasible adoption scenario than the real options revenue threshold.

Inhibiting Crop Insurance Scenarios

Although results from the benchmark model show crop insurance is only slightly affecting DWR adoption, there are scenarios where crop insurance could inhibit DWR adoption. In the year 2012, producers received large crop insurance payments because of a drought. In Indiana, producers received an average revenue protection insurance net payout of $240 per acre (RMA, 2018). Although the large drought crop insurance payments happen infrequently, climate change could cause droughts to become more frequent and large crop insurance payments to occur more regularly. Using the $240 per acre value for the expected change in net crop insurance payout from adopting DWR in the feasible DWR scenario results in revenue thresholds of $608 per acre when crop insurance is not in effect and $856 when crop insurance is in effect. The producer would adopt DWR when crop insurance is not in effect and wait to adopt DWR when crop insurance is in effect. The difference between the revenue thresholds is $248 per acre. Applying the $240 net change in crop insurance payout parameter to the feasible DWR adoption scenario NPV model results in revenue thresholds of $12 per acre when crop insurance is not in effect and $16 per acre when crop insurance is in effect. Crop insurance is not inhibiting DWR adoption in the NPV model.

The drought crop insurance scenario is also applied to the benchmark DWR adoption scenario listed in Table 4 below. When the net change in expected crop insurance is $240 per acre in the benchmark scenario, the revenue threshold is $1,175 per acre when crop insurance is not in effect and $1,392 per acre when crop insurance is in effect. The revenue thresholds are much higher than the conventional revenue, and the difference between the thresholds is $217 per acre. Applying the drought crop insurance scenario to the benchmark NPV model results in a revenue threshold of $810 per acre when crop insurance is not in effect and $909 per acre when crop insurance is in effect.

The standard deviation of the net payout for all coverage levels of Indiana revenue protection crop insurance is 90. Applying the standard deviation value for the expected net change in the crop insurance payout from adopting DWR to the real options feasible DWR adoption scenario results in revenue thresholds of $638 per acre when crop insurance is not in effect and $709 per acre when crop insurance is in effect, so the producer would adopt DWR when crop insurance is not in effect and wait to adopt DWR when crop insurance is in effect. Applying the standard deviation value of 90 to the feasible NPV DWR adoption model results in revenue thresholds of $12 per acre when crop insurance is not in effect and $13 per acre when crop insurance is in effect, so the producer will adopt when crop insurance is and is not in effect. Applying the standard deviation value of 90 to the real options benchmark model results in revenue thresholds of $1,288 per acre when crop insurance is not in effect and $1,368 per acre when crop insurance is in effect. Applying the standard deviation value of 90 to the NPV benchmark model results in revenue thresholds of $810 per acre when crop insurance is not in effect and $847 per acre when crop insurance is in effect.

There are scenarios where crop insurance inhibits the adoption of DWR, but they are unlikely to occur. In a drought, DWR is likely ineffective because the water in the pond evaporates and is not replenished. DWR is most effective for short summer dry periods. It is also unlikely for a drought to occur every year and for producers to receive crop insurance payouts of $240 per acre each year.

Conclusion and Policy Implications

The benchmark DWR adoption model suggests producers will not invest in DWR in the current time interval. The revenue thresholds required to invest in DWR are much larger than current or historic revenue levels. One reason the DWR investment is infeasible is the immense sunk and variable cost of the system. The DWR system cost is very large, but DWR is only mitigating climate-change risk on a small portion of the producer's total acres. The producer is making a large investment and only getting a small benefit. Farm level climate-change adaption technologies such as drought resistant seeds or precision technology could be more feasible for the producer. If a producer already has part of the DWR system in place, such as the pond or irrigation system, this could make DWR adoption more feasible for the producer by lowering the large sunk cost of DWR investment.

Another reason the model suggests waiting to invest in DWR is because the benchmark DWR revenue drift and volatility are very similar to the conventional revenue drift and volatility. The crop simulation models do not show a very large difference between DWR yield and conventional yield with climate change. Currently, the variable cost is greater than the yearly increase in yield from having irrigation. If climate change is worse than expected or if the difference between DWR and conventional yield is greater than the crop simulation model currently predicts, then the DWR investment would become more valuable. With regards to climate change, DWR is effective in short term summer dry periods, but if climate change causes droughts to become more frequent, then DWR will be ineffective. In a drought situation, there is not enough water in the pond to irrigate. If long droughts become more frequent, then DWR will most likely be ineffective. If short dry periods become more frequent, then DWR possibly becomes a feasible climate-change adaption strategy.

DWR has potential societal benefits. By capturing drained water from fields, the DWR system reduces nutrient runoff into water systems and reduces the negative externalities of production agriculture. This analysis focuses solely on the DWR adoption decision from the producer's viewpoint and does not consider the monetary value of the societal benefits of DWR adoption. If the producer could internalize the monetary value of the societal benefits, this would positively influence DWR adoption.

Policy makers should not consider a subsidy of the sunk or variable cost of DWR in this time interval because both are costs close to inelastic. A large decrease in sunk or variable cost only results in a small decrease of the revenue thresholds. In the benchmark DWR adoption scenario, subsidizing DWR is not effective and will not cause producers to adopt the technology with the current climate change projections. Policy makers should also consider that crop insurance does influence the adoption of DWR, but the effects are very small and not inhibiting the adoption of DWR. DWR and crop insurance are not substitutes. They are managing two different type of loss: shallow loss and deep loss. DWR is more effective for shallow loss, such as short summer dry periods which cause a decrease in yield. Crop insurance manages deep loss, which is where the whole crop is significantly reduced or wiped out, such as during a drought or natural disaster. Producers will most likely not base their DWR investment decision on whether or not crop insurance is in effect. DWR is a niche climate-adaption strategy. There are likely some scenarios where DWR could be feasible in the future.

Another aspect policy makers need to consider is there are times when NPV analysis suggests investing in DWR and real options suggests waiting. If policy makers base policies on NPV analysis instead of the more robust real options analysis, then the policies will be incorrect. There is a large difference between NPV and real options analysis in all aspects of this research, with real options always being much higher than NPV. Policy makers should consider more robust analysis methods such as real options analysis when making policy decisions.

Other climate-adaptation practices may be more feasible for producers. Such adaptations typically fall into one of four categories: technological developments, government programs and insurance, farm production practices, and farm financial management. Most adaptations are modifications of current farm practices and policies. Understanding the relationship between adaption options and current practices is essential for progress on implementing adaptations (Smit and Skinner, 2002). Adaptations which are low or no cost to the producer and easy to implement should be further investigated.

In most cases, DWR is unlikely to be financially feasible at this time. Producers and policy makers need to consider this when making the DWR investment decision or setting policy. A quote from Monast et. al. (2018) states: “Agriculture sustainability advocates need to be invested in the overall financial success of farmers and change course when conservation adoption does not help farmers remain viable.” In the current time interval, policy makers and producers should shift their focus to climate-change adaption practices which are financially feasible.

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Table 1. Results for the Augmented Dickey-Fuller Unit-Root Test

	Test Statistic	Mackinnon Approximate p-value
Indiana Corn Price Received, $/bu, 1984-2013	−0.3601	0.5112
Indiana West Central Region Non-Irrigated Yield, bu/acre, 1984-2013	−0.0950	0.6079
Indiana West Central Region Irrigated Yield, bu/acre, 1984-2013	−0.0846	0.6117
Indiana West Central Region Non-Irrigated Yield, bu/acre, 2041-2070	−0.1180	0.5995
Indiana West Central Region Irrigated Yield, bu/acre, 2041-2070	−0.0953	0.6078

Table 2. West-Central Indiana Impounded DWR 160 Acre Field Benchmark Cost Scenario

	Total Cost	$/acre
Construction	$671000	$5083
NRCS, 2018		
Land	96,000	727
PAER, 2018		
Pivot	75,000	568
Kelley, 2018		
Pumping Plant	18,000	136
Dahl, Personal Communication, 2018		
Sunk Cost	**$860000**	**$6515**
Diesel	2000	15
EIA, 2018		
Labor	3000	23
NASS, 2013		
Variable Cost	**$5000**	**$38**

Table 3. Indiana Revenue Protection (RP) Crop Insurance Averages per Coverage Level, 2011-2017

Coverage Level	Average Producer Premium (per acre)	Average Total Premium (per acre)	Average Subsidy (per acre)	Average Indemnity (per acre)	Average Net Payout (per acre)	Average Net Payout per Acre (no subsidy)
50%	$5.53	$19.29	$13.76	$25.52	$19.99	$6.23
55	8.89	26.41	17.52	31.37	22.48	4.97
60	16.75	48.57	31.83	57.36	40.61	8.79
65	14.77	39.94	25.17	58.29	43.52	18.35
70	19.70	53.68	33.97	72.28	52.58	18.60
75	18.02	51.58	33.56	65.83	47.81	14.25
80	19.25	49.83	30.58	64.99	45.74	15.16
85	26.14	51.38	25.24	77.44	51.31	26.07

Source: RMA, 2018

Table 4. Benchmark Values and Parameter Ranges for Real Options DWR Model

Parameter	Symbol	Benchmark	Range Lower	Range Upper
Price Drift	α_p	0.026		
Price Volatility	σ_p	0.241		
Conventional Yield Drift	α_C	0.011		
Conventional Yield Volatility	σ_C	0.122		
Correlation between Price and Conventional Yield	ρ_C	−0.247		
DWR Yield Drift	α_D	0.011		
DWR Yield Volatility	σ_D	0.120		
Correlation between Price and DWR Yield	ρ_D	−0.264		
Conventional Revenue Drift	α_{RC}	0.030	0.000	0.040
Conventional Revenue Volatility	σ_{RC}	0.242	0.000	0.500
DWR Revenue Drift	α_{RD}	0.029	0.000	0.040
DWR Revenue Volatility	σ_{RD}	0.239	0.000	0.500
Correlation coefficient between the uncertainty incorporated in the change of the two revenues	ρ_R	0.900	0.000	0.990
Revenue Volatility	σ_R	0.012		
Discount Rate (percent)	r	5.00	4.00	10.00
Variable cost of adopting DWR (dollars/acre)	V	38.00	25.00	260.00
Sunk cost of adopting DWR (dollars/acre)	I	6515	3500	9300
Probability of no indemnity in the next time interval	λ_0	0.010	0.010	0.400
Probability of an indemnity in the next time interval	λ_1	0.010	0.010	0.400
Change in expected net insurance payout from adopting DWR (dollars/acre)	Θ	0.00	−30.00	30.00
Conventional Revenue (dollars/acre)	Rc	649		

Table 4 continued

The difference between the expected rate of return and the expected capital gain with no DWR.	δ_C	0.020
The difference between the expected rate of return and the expected capital gain with DWR.	δ_D	0.021

Table 5. Benchmark Values and Parameter Ranges for NPV DWR Model

Parameter	Symbol	Benchmark	Range Lower	Range Upper
Price Drift	α_p	0.026		
Price Volatility	σ_p	0.241		
Conventional Yield Drift	α_C	0.011		
Conventional Yield Volatility	σ_C	0.122		
Correlation between Price and Conventional Yield	ρ_C	−0.247		
DWR Yield Drift	α_D	0.011		
DWR Yield Volatility	σ_D	0.120		
Correlation between Price and DWR Yield	ρ_D	−0.264		
Conventional Revenue Drift	α_{RC}	0.030	0.000	0.040
DWR Revenue Drift	α_{RD}	0.029	0.000	0.040
Discount Rate (percent)	r	5.00	4.00	10.00
Variable cost of adopting DWR (dollars/acre)	V	38.00	25.00	260.00
Sunk cost of adopting DWR (dollars/acre)	I	6515	3500	9300
Change in expected net insurance payout from adopting DWR (dollars/acre)	Θ	0.00	−30.00	30.00
Conventional Revenue (dollars/acre)	Rc	649		
The difference between the expected rate of return and the expected capital gain with no DWR.	δ_C	0.020		
The difference between the expected rate of return and the expected capital gain with DWR.	δ_D	0.021		

Table 6. Real Options and NPV Benchmark Results for Different Levels of Change in Expected Net Crop Insurance Payout

	$\theta = \$30$	$\theta = \$0$	$\theta = -\$30$
Real Options			
Revenue ratio when crop insurance is not in effect (ω_0)	2.06	2.09	2.13
Revenue ratio when crop insurance is in effect (ω_1)	2.10	2.09	2.09
Revenue threshold when crop insurance is not in effect (R_D^0)	$1334	$1358	$1382
Revenue threshold when crop insurance is in effect (R_D^1)	$1361	$1358	$1355
NPV			
Revenue ratio when crop insurance is not in effect (ω_{NPV0})	1.25	1.25	1.25
Revenue ratio when crop insurance is in effect (ω_{NPV1})	1.26	1.25	1.23
Revenue threshold when crop insurance is not in effect (NPV_0)	$810	$810	$810
Revenue threshold when crop insurance is in effect (NPV_1)	$822	$810	$797

Table 7. Comparison between Real Options, NPV, and Conventional Revenue for Different Levels of Expected Net Crop Insurance Payout

	Difference Between ROA and NPV Revenue Threshold ($/acre)	Difference between ROA and NPV Revenue Threshold (%)	Difference between ROA and Conventional Revenue ($/acre)	Difference between ROA and Conventional Revenue (%)
$\theta = \$30$				
No Crop Insurance	524	65	685	106
Crop Insurance	539	66	712	110
$\theta = \$0$				
No Crop Insurance	548	68	709	109
Crop Insurance	548	68	709	109
$\theta = -\$30$				
No Crop Insurance	572	71	733	113
Crop Insurance	558	70	706	109

Table 8. Per Acre Revenue Threshold when Crop Insurance is in not in Effect (R_D^0) and Change in Expected Net Insurance Payment (θ) is \$30 per acre

λ_1^a								
λ_0^b	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40
0.05	1,327	1,329	1,330	1,331	1,331	1,332	1,332	1,333
0.10	1,320	1,322	1,324	1,325	1,326	1,327	1,328	1,329
0.15	1,314	1,317	1,319	1,321	1,322	1,324	1,325	1,326
0.20	1,310	1,312	1,315	1,317	1,319	1,320	1,322	1,323
0.25	1,306	1,309	1,311	1,313	1,315	1,317	1,319	1,321
0.30	1,303	1,306	1,308	1,311	1,313	1,315	1,317	1,319
0.35	1,300	1,303	1,305	1,308	1,310	1,313	1,315	1,317
0.40	1,297	1,300	1,303	1,306	1,308	1,311	1,313	1,316

[a] $\lambda_1 dt$ denotes the probability of an indemnity in the next time interval if no indemnity occurs this time interval.

[b] $\lambda_0 dt$ denotes the probability of no indemnity in the next time interval if there is an indemnity in this time interval.

Table 9. Per Acre Revenue Threshold when Crop Insurance is in Effect (R_D^1) and Change in Expected Net Insurance Payment (θ) is $30 per acre

λ_1^a								
λ_0^b	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40
0.05	1,370	1,380	1,389	1,398	1,407	1,416	1,427	1,439
0.10	1,369	1,379	1,388	1,397	1,406	1,416	1,427	1,440
0.15	1,368	1,378	1,387	1,396	1,405	1,415	1,427	1,441
0.20	1,368	1,377	1,386	1,395	1,404	1,415	1,427	1,442
0.25	1,367	1,376	1,385	1,394	1,404	1,415	1,427	1,444
0.30	1,367	1,376	1,385	1,394	1,404	1,415	1,428	1,446
0.35	1,367	1,376	1,385	1,394	1,404	1,415	1,429	1,449
0.40	1,367	1,375	1,384	1,393	1,404	1,415	1,430	1,453

[a] $\lambda_1 dt$ denotes the probability of an indemnity in the next time interval if no indemnity occurs this time interval.

[b] $\lambda_0 dt$ denotes the probability of no indemnity in the next time interval if there is an indemnity in this time interval.

Table 10. Per Acre Revenue Threshold when Crop Insurance is in not in Effect (R_D^0) and Change in Expected Net Insurance Payment (θ) is $-\$30$ per acre

λ_1^a								
λ_0^b	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40
0.05	1,391	1,390	1,389	1,388	1,388	1,388	1,387	1,387
0.10	1,401	1,399	1,398	1,397	1,396	1,396	1,395	1,395
0.15	1,409	1,408	1,406	1,405	1,405	1,404	1,403	1,403
0.20	1,418	1,416	1,415	1,414	1,413	1,412	1,411	1,411
0.25	1,426	1,424	1,423	1,422	1,421	1,420	1,419	1,419
0.30	1,433	1,432	1,431	1,430	1,429	1,428	1,427	1,426
0.35	1,441	1,440	1,439	1,438	1,437	1,436	1,435	1,434
0.40	1,449	1,448	1,447	1,446	1,445	1,444	1,443	1,443

[a] $\lambda_1 dt$ denotes the probability of an indemnity in the next time interval if no indemnity occurs this time interval.

[b] $\lambda_0 dt$ denotes the probability of no indemnity in the next time interval if there is an indemnity in this time interval.

Table 11. Per Acre Revenue Threshold when Crop Insurance is in in Effect (R_D^1) and Change in Expected Net Insurance Payment (θ) is $-\$30$ per acre

λ_1^a								
λ_0^b	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40
0.05	1,348	1,340	1,335	1,330	1,326	1,322	1,319	1,316
0.10	1,349	1,343	1,337	1,332	1,328	1,325	1,322	1,319
0.15	1,350	1,344	1,339	1,334	1,331	1,327	1,324	1,321
0.20	1,351	1,345	1,340	1,336	1,332	1,329	1,326	1,323
0.25	1,352	1,346	1,342	1,338	1,334	1,331	1,328	1,325
0.30	1,352	1,347	1,343	1,339	1,336	1,333	1,330	1,327
0.35	1,353	1,348	1,344	1,340	1,337	1,334	1,331	1,329
0.40	1,353	1,349	1,345	1,342	1,338	1,336	1,333	1,331

[a] $\lambda_1 dt$ denotes the probability of an indemnity in the next time interval if no indemnity occurs this time interval.

[b] $\lambda_0 dt$ denotes the probability of no indemnity in the next time interval if there is an indemnity in this time interval.

Table 12. Monte Carlo results for real options DWR revenue thresholds when crop insurance is not in effect and when crop insurance is in effect

Level, R_D^0, R_D^1 (dollars/acre)	Probability R*< R_D^0	Probability R*< R_D^1
0	0.0000	0.0002
324	0.0000	0.0010
649	0.0048	0.0012
973	0.0104	0.0048
1,297	0.0344	0.0282
1,622	0.1058	0.0986
1,946	0.2106	0.2036
2,270	0.3238	0.3172
2,594	0.4412	0.4334
2,919	0.5480	0.5386
3,243	0.6426	0.6332
3,567	0.7270	0.7146
3,892	0.7930	0.7828
4,216	0.8488	0.8364
4,540	0.8866	0.8772
4,865	0.9168	0.9046
5,189	0.9358	0.9238
5,513	0.9490	0.9376
5,837	0.9588	0.9466
6,162	0.9654	0.9552
6,486	0.9702	0.9600
$>$ 6,486	1.0000	1.0000

Table 13. Monte Carlo results for NPV DWR revenue thresholds when crop insurance is not in effect and when crop insurance is in effect

Level, NPV_0, NPV_1 (dollars/acre)	Probability R*$< NPV_0$	Probability R*$< NPV_1$
0	0.0000	0.0000
324	0.0174	0.0172
649	0.1092	0.1080
973	0.3618	0.3632
1,297	0.6994	0.6988
1,622	0.8924	0.8934
1,946	0.9626	0.9614
2,270	0.9804	0.9810
2,594	0.9890	0.9888
2,919	0.9930	0.9930
3,243	0.9952	0.9952
3,567	0.9956	0.9954
3,892	0.9968	0.9966
4,216	0.9972	0.9972
4,540	0.9988	0.9986
4,865	0.9992	0.9992
5,189	0.9992	0.9992
5,513	0.9994	0.9994
5,837	0.9994	0.9994
6,162	0.9996	0.9996
6,486	0.9998	0.9998
$>$ 6,486	1.0000	1.0000

Table 14. Feasible DWR Adoption Scenario for Real Options Model

Parameter	Symbol	Value
Conventional Revenue Drift	α_{RC}	0.000
Conventional Revenue Volatility	σ_{RC}	0.210
DWR Revenue Drift	α_{RD}	0.057
DWR Revenue Volatility	σ_{RD}	0.220
Correlation coefficient between the uncertainty incorporated in the change of the two revenues	ρ_R	0.900
Revenue Volatility	σ_R	0.009
Discount Rate (percent)	r	5.80
Variable cost of adopting DWR (dollars/acre)	V	25.00
Sunk cost of adopting DWR (dollars/acre)	I	0
Probability of no indemnity in the next time interval	λ_0	0.300
Probability of an indemnity in the next time interval	λ_1	0.010
Change in expected net insurance payout from adopting DWR (dollars/acre)	Θ	30.00
Conventional Revenue (dollars/acre)	Rc	649
The difference between the expected rate of return and the expected capital gain with no DWR.	δ_C	0.058
The difference between the expected rate of return and the expected capital gain with DWR.	δ_D	0.001

Table 15. Feasible DWR Adoption Scenario for NPV Model

Parameter	Symbol	Value
Conventional Revenue Drift	α_{RC}	0.000
DWR Revenue Drift	α_{RD}	0.057
Discount Rate (percent)	r	5.80
Variable cost of adopting DWR (dollars/acre)	V	25.00
Sunk cost of adopting DWR (dollars/acre)	I	0
Change in expected net insurance payout from adopting DWR (dollars/acre)	Θ	30.00
Conventional Revenue (dollars/acre)	Rc	649
The difference between the expected rate of return and the expected capital gain with no DWR.	δ_C	0.058
The difference between the expected rate of return and the expected capital gain with DWR.	δ_D	0.001

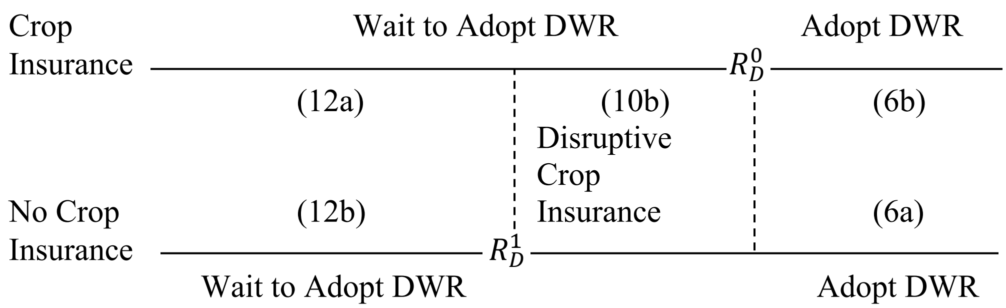

Figure 1. Revenue thresholds for DWR adoption

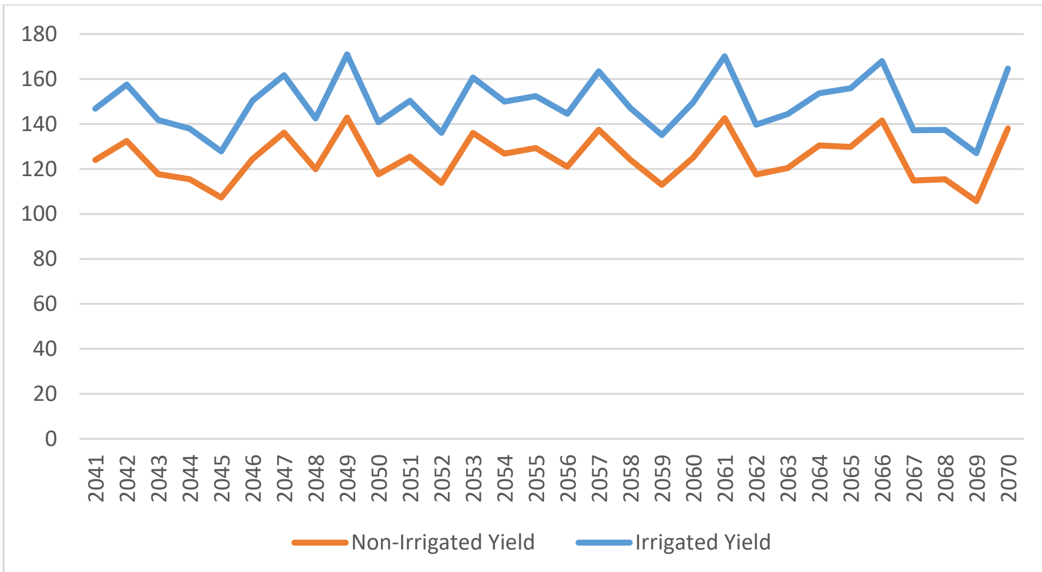

Figure 2. West-central Indiana non-irrigated and irrigated future corn yield, 2041-2070

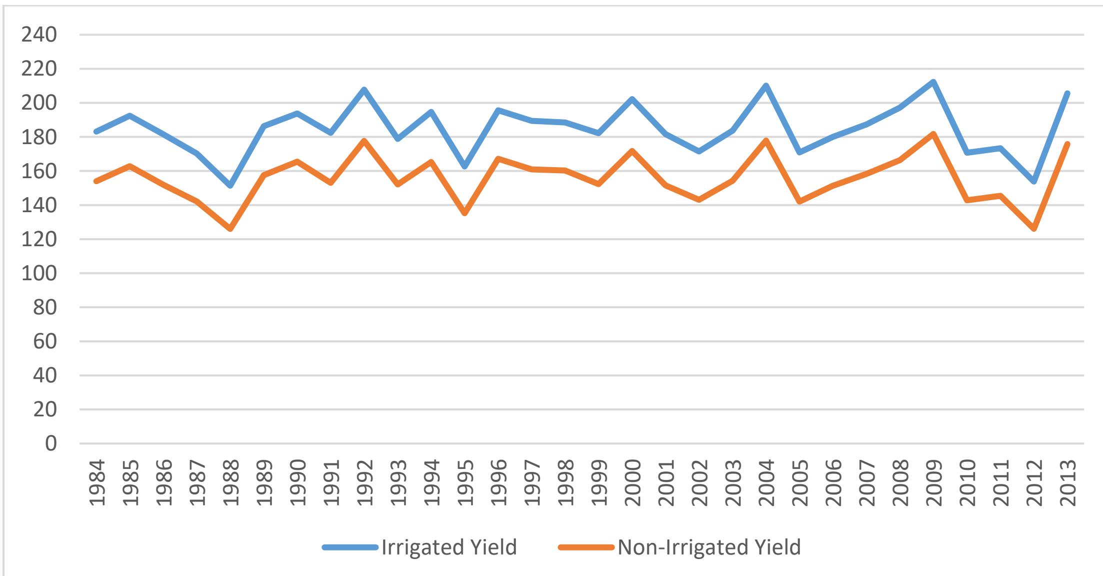

Figure 3. West-central Indiana non-irrigated and irrigated historic corn yield, 1984-2013

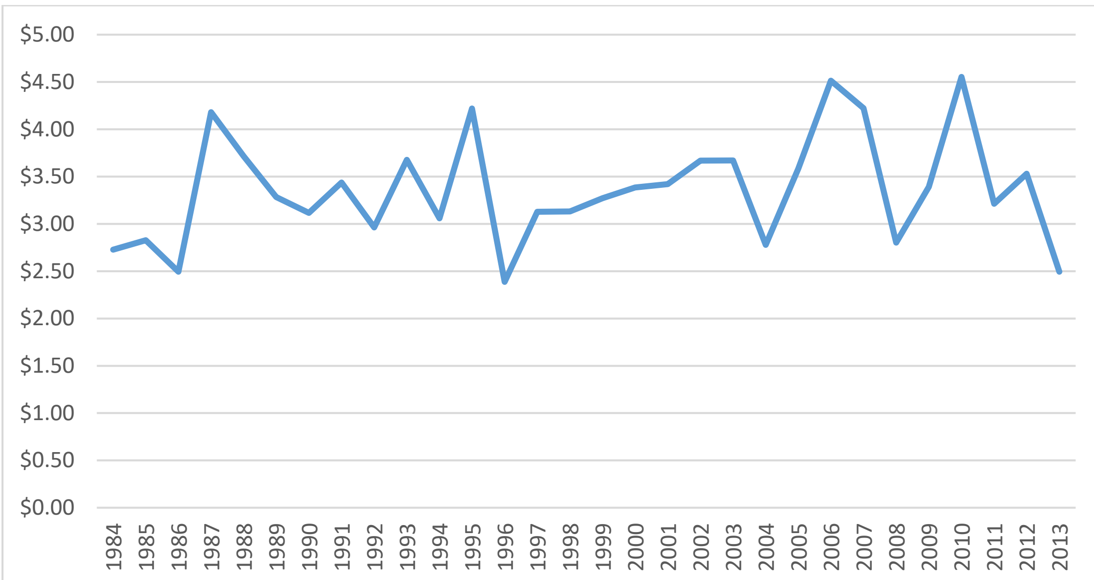

Figure 4. Deflated Indiana corn prices, 1984-2013

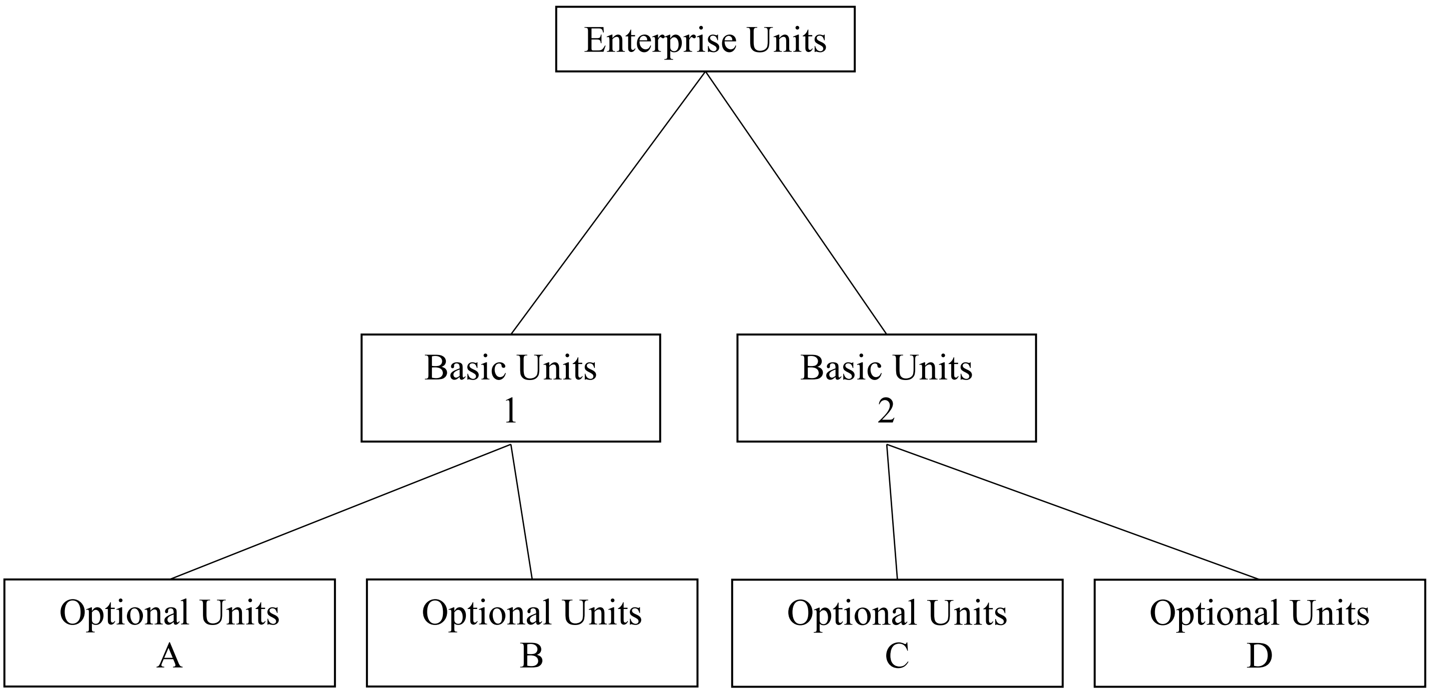

Figure 5. Crop insurance unit structure

Crop	R_D^0	Wait →	\$1358	Adopt →
Insurance	NPV^0	Wait → \$810	Adopt →	
No Crop	R_D^1	Wait →	\$1358	Adopt →
Insurance	NPV^1	Wait → \$810	Adopt →	

Figure 6. Real Options (R_D^0, R_D^1) and NPV (NPV^0, NPV^1) DWR adoption thresholds: zero net change in insurance payout

Crop	R_D^0	—— Wait ——→ \$1361 —— Adopt ——→
Insurance	NPV^0	—— Wait ——→ \$822 —— Adopt ——→
No Crop	R_D^1	—— Wait ——→ \$1334 —— Adopt ——→
Insurance	NPV^1	—— Wait ——→ \$810 —— Adopt ——→

Figure 7. Real Options (R_D^0, R_D^1) and NPV (NPV^0, NPV^1) DWR adoption thresholds: \$30 net change in insurance payout

Crop	R_D^0	—— Wait ——→ \$1355 —— Adopt ——→
Insurance	NPV^0	—— Wait → \$797 —— Adopt ——→
No Crop	R_D^1	—— Wait ——→ \$1382 Adopt ——→
Insurance	NPV^1	—— Wait → \$810 —— Adopt ——→

Figure 8. Real Options (R_D^0, R_D^1) and NPV (NPV^0, NPV^1) DWR adoption thresholds: $-$\$30 net change in insurance payout

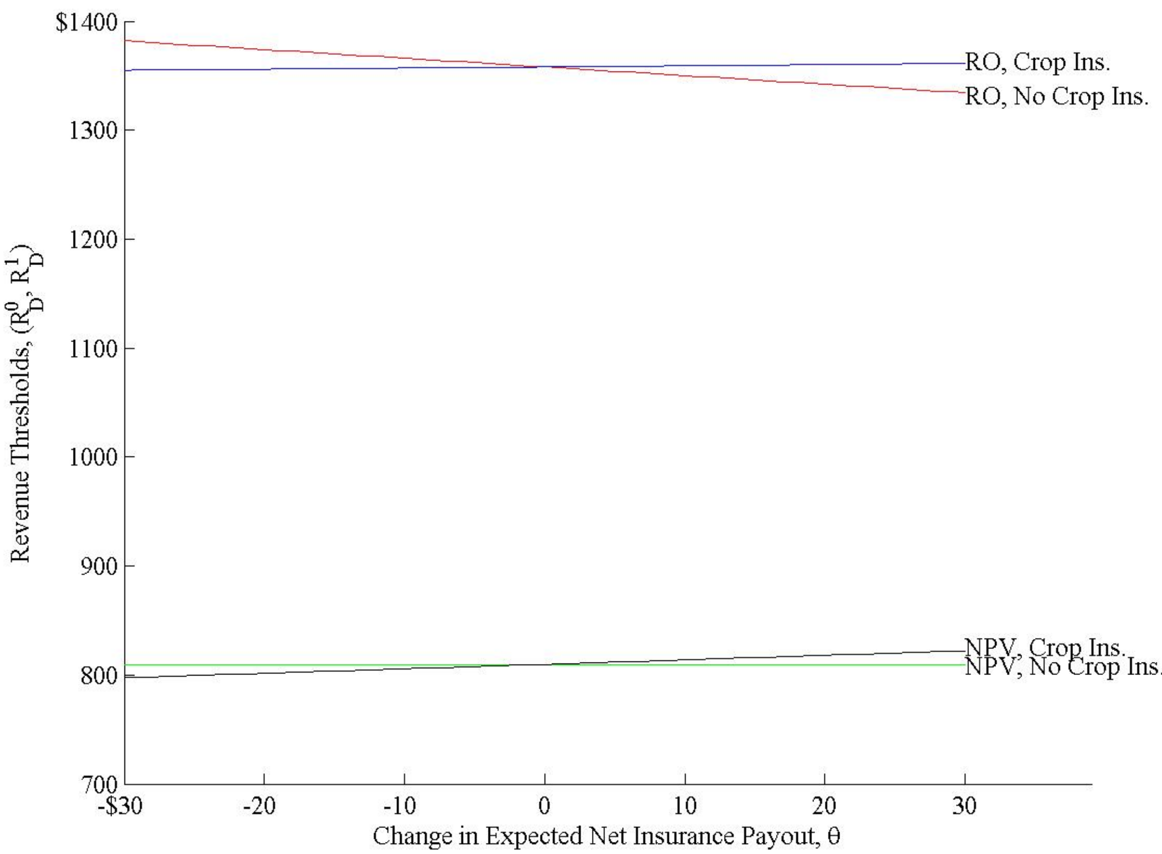

Figure 9. Response of revenue thresholds to the change in expected net insurance payout from adopting DWR

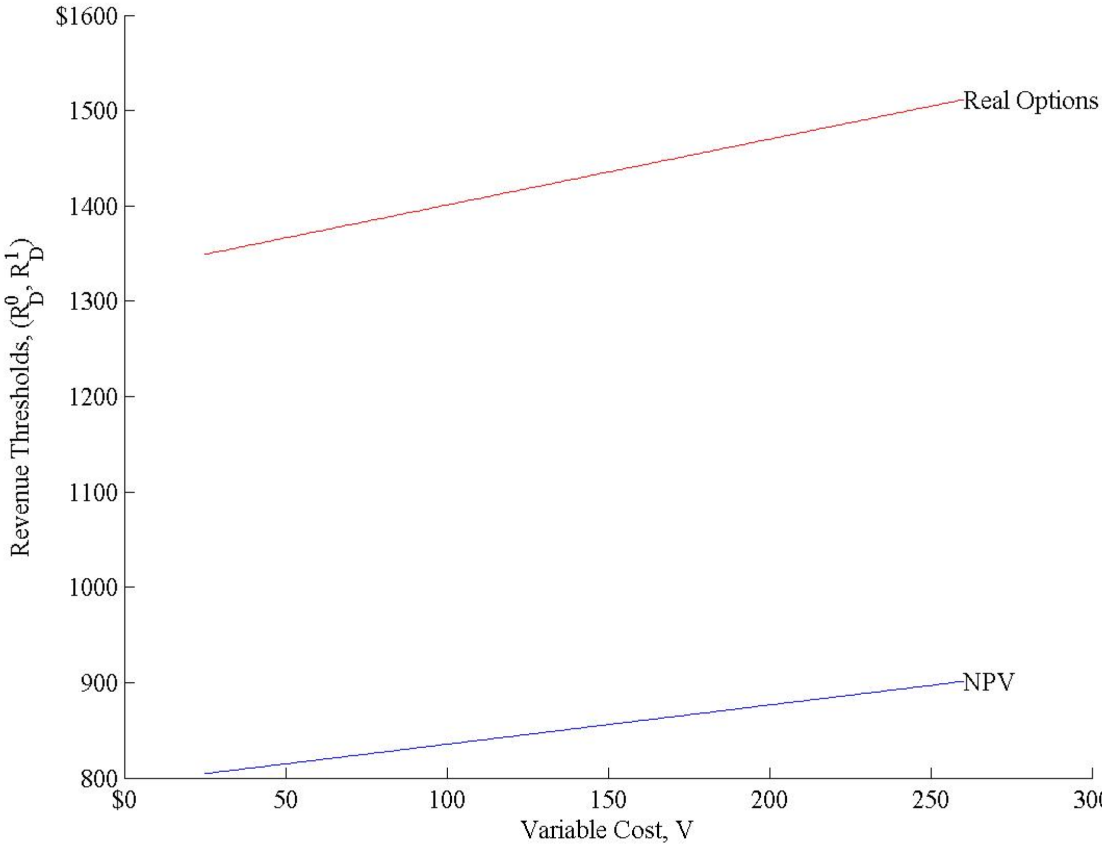

Figure 10. Response of revenue threshold to variable cost

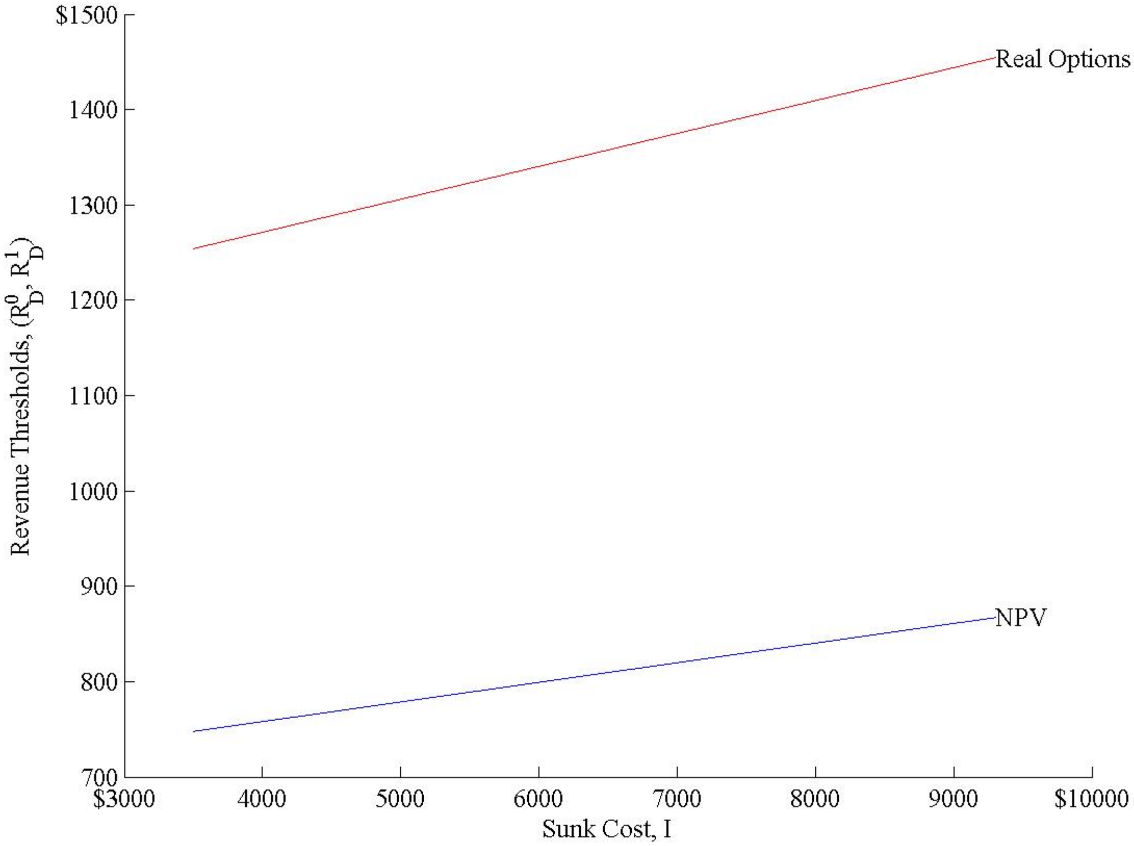

Figure 11. Response of revenue threshold to sunk cost

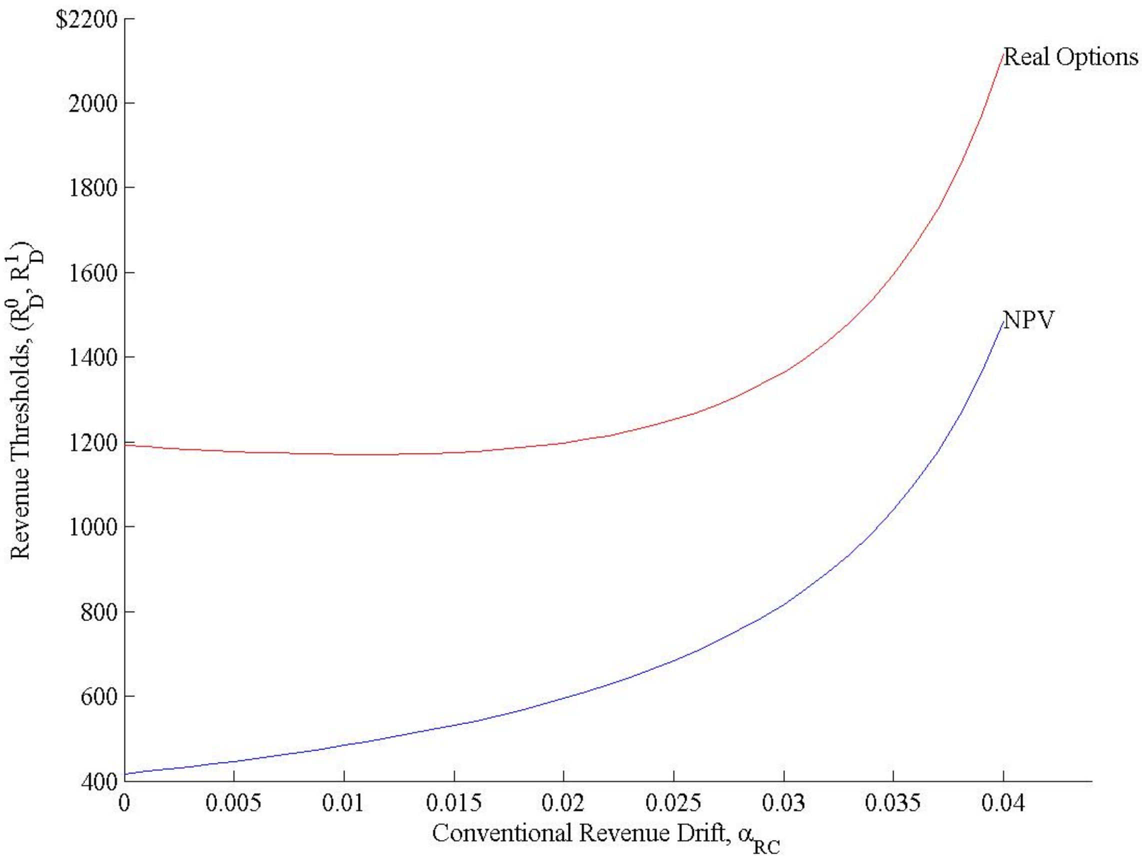

Figure 12. Response of revenue threshold to conventional revenue drift

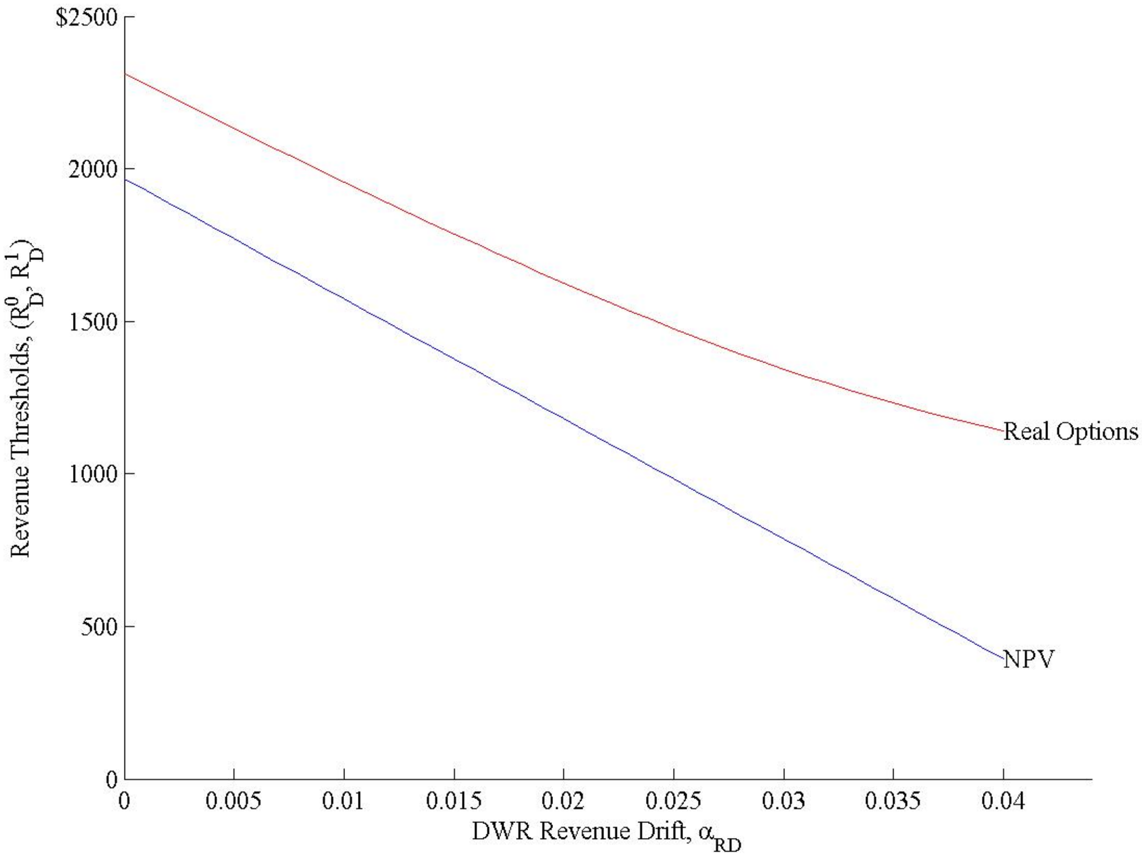

Figure 13. Response of revenue threshold to DWR revenue drift

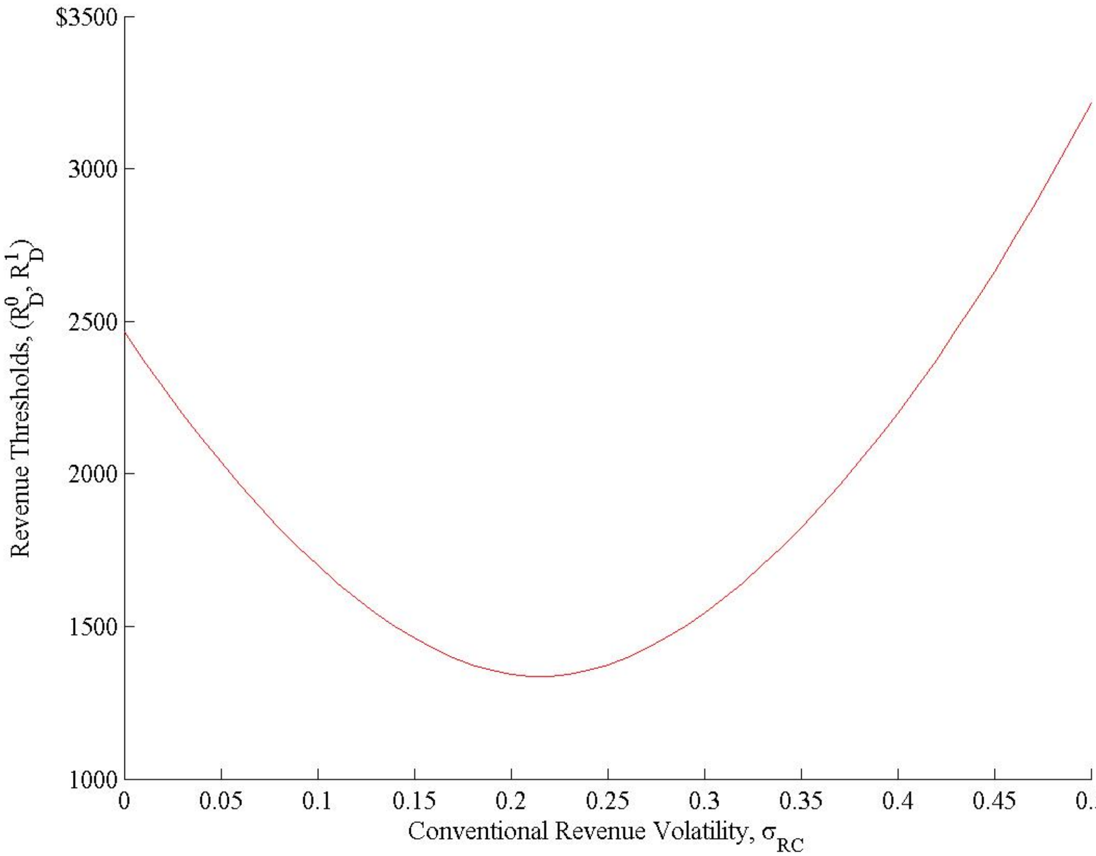

Figure 14. Response of revenue threshold to conventional revenue volatility

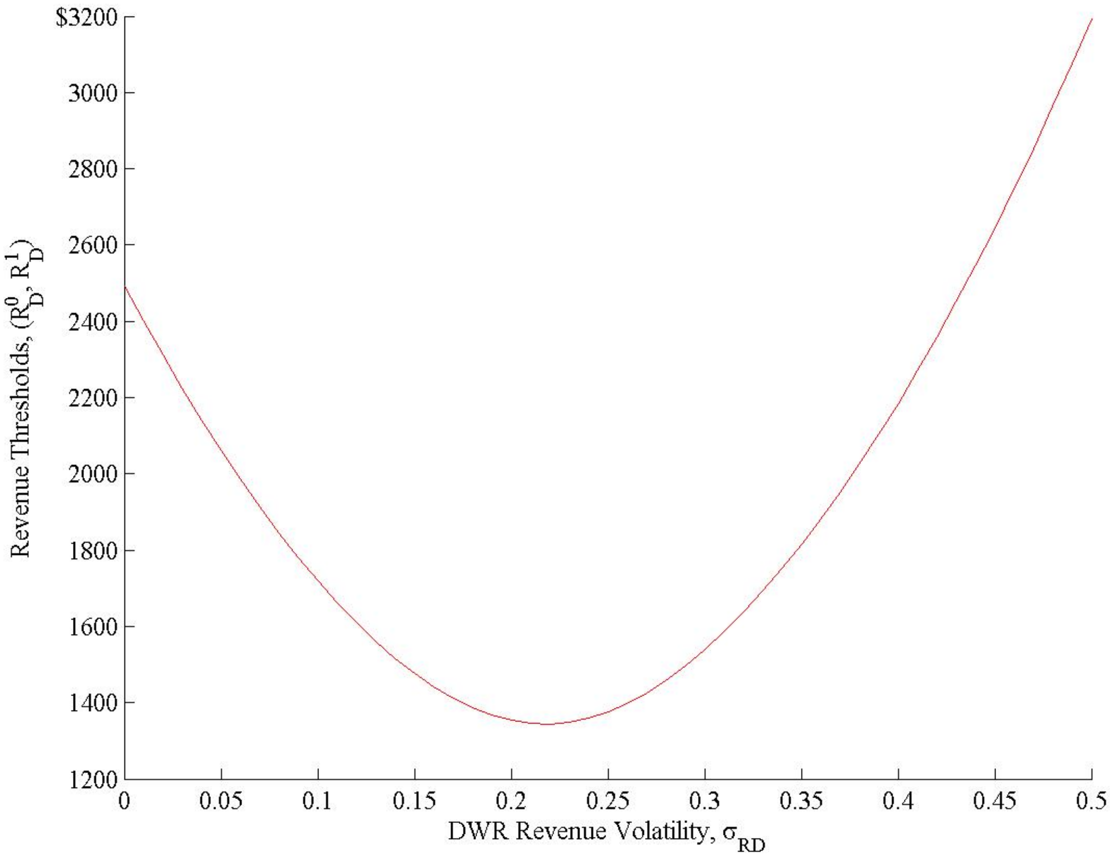

Figure 15. Response of revenue threshold to DWR revenue volatility

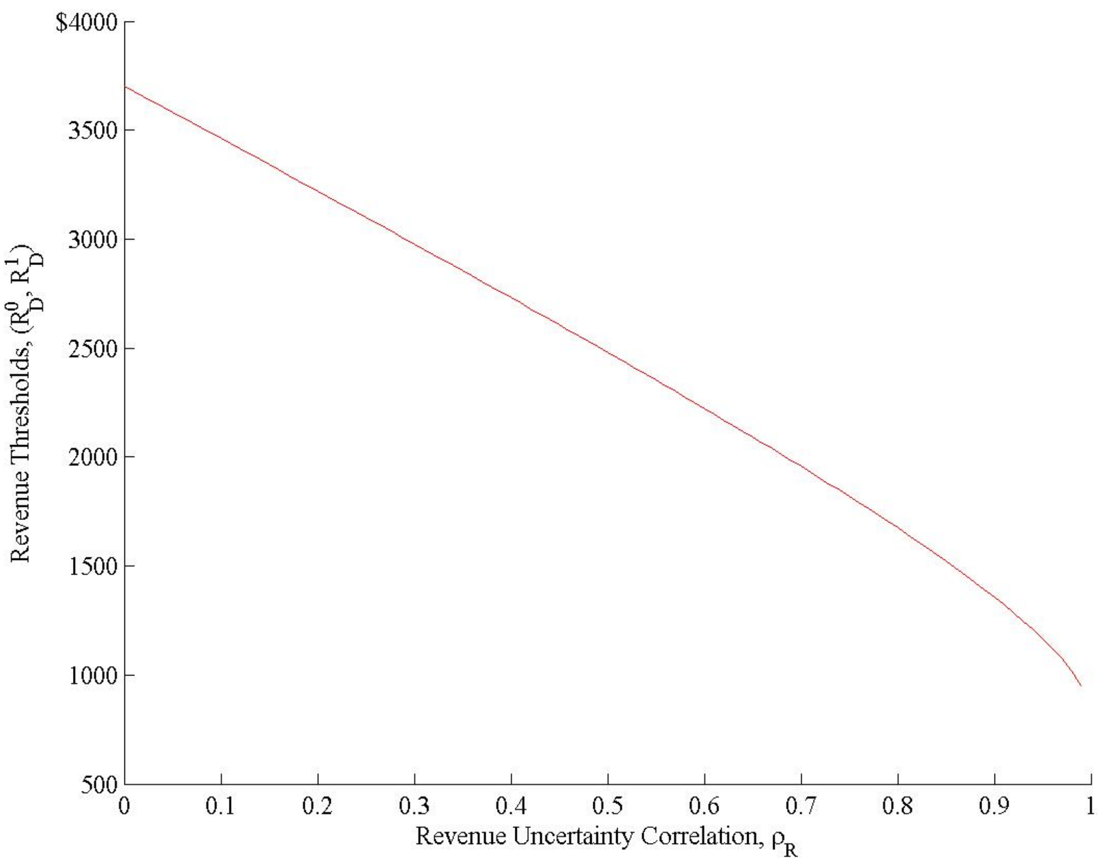

Figure 16. Response of revenue threshold to correlation coefficient between the uncertainty incorporated in the change of the two revenues

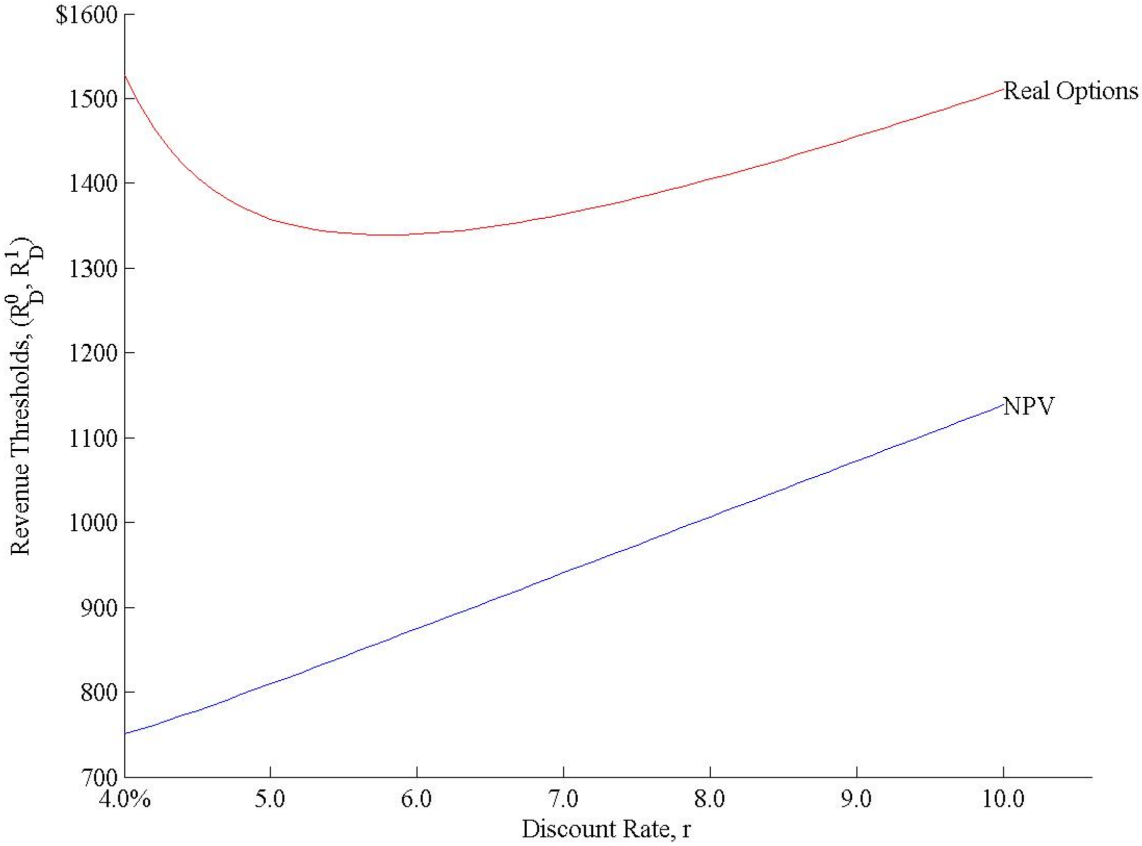

Figure 17. Response of revenue threshold to the discount rate

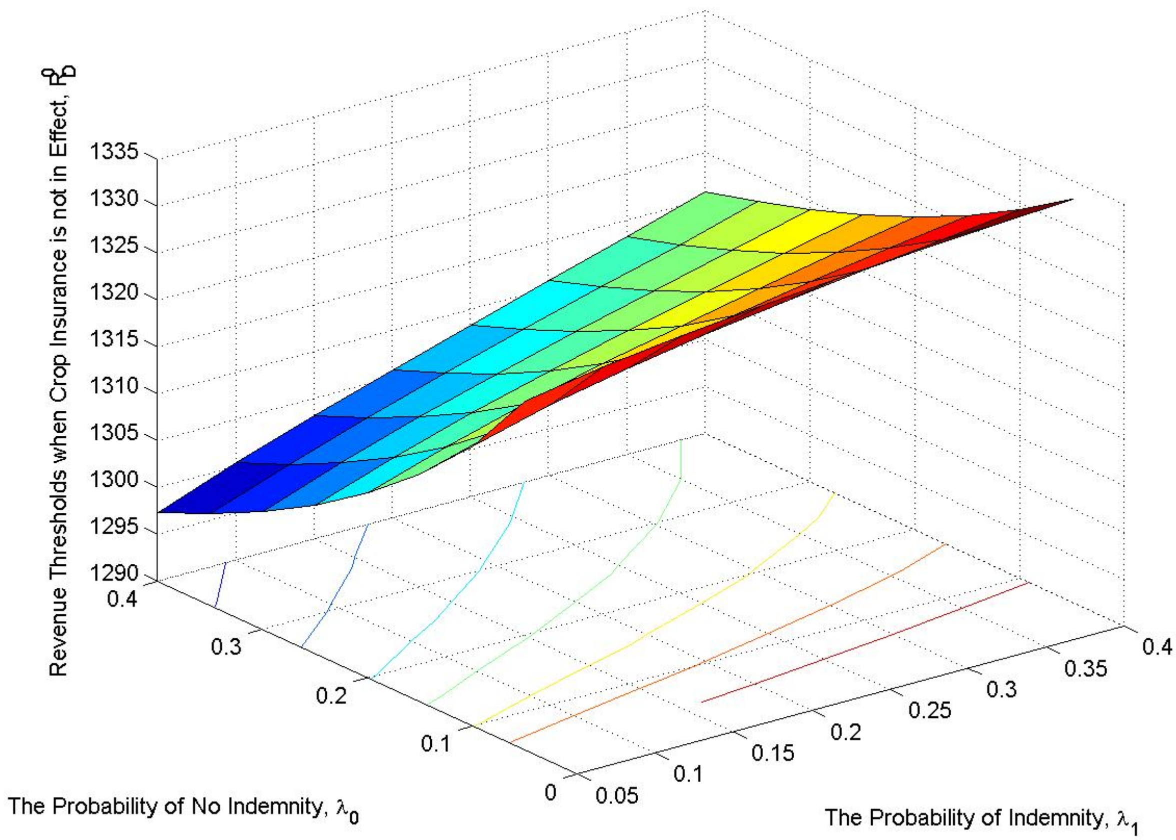

Figure 18. Revenue thresholds when crop insurance is not in effect (R_D^0) and $\theta = 30$

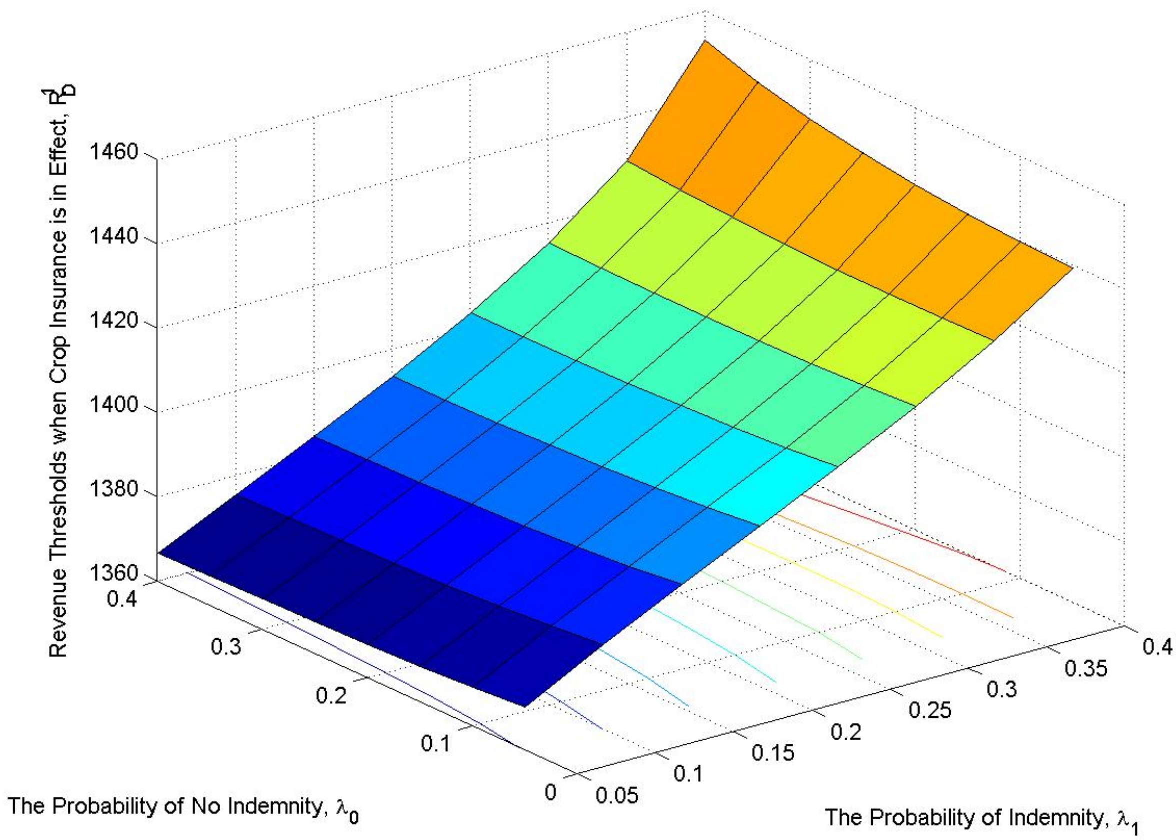

Figure 19. Revenue thresholds when crop insurance is in effect (R_D^1) and $\theta = 30$

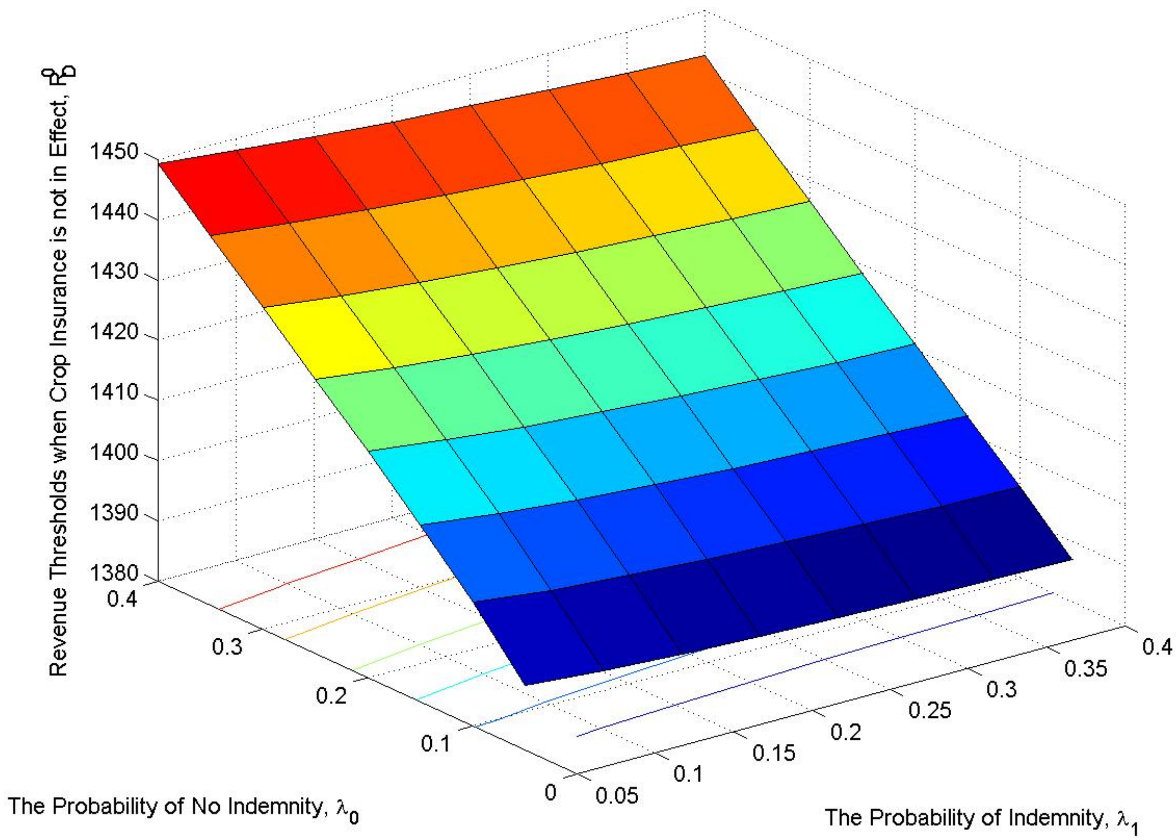

Figure 20. Revenue thresholds when crop insurance is not in effect (R_D^0) and $\theta = -30$

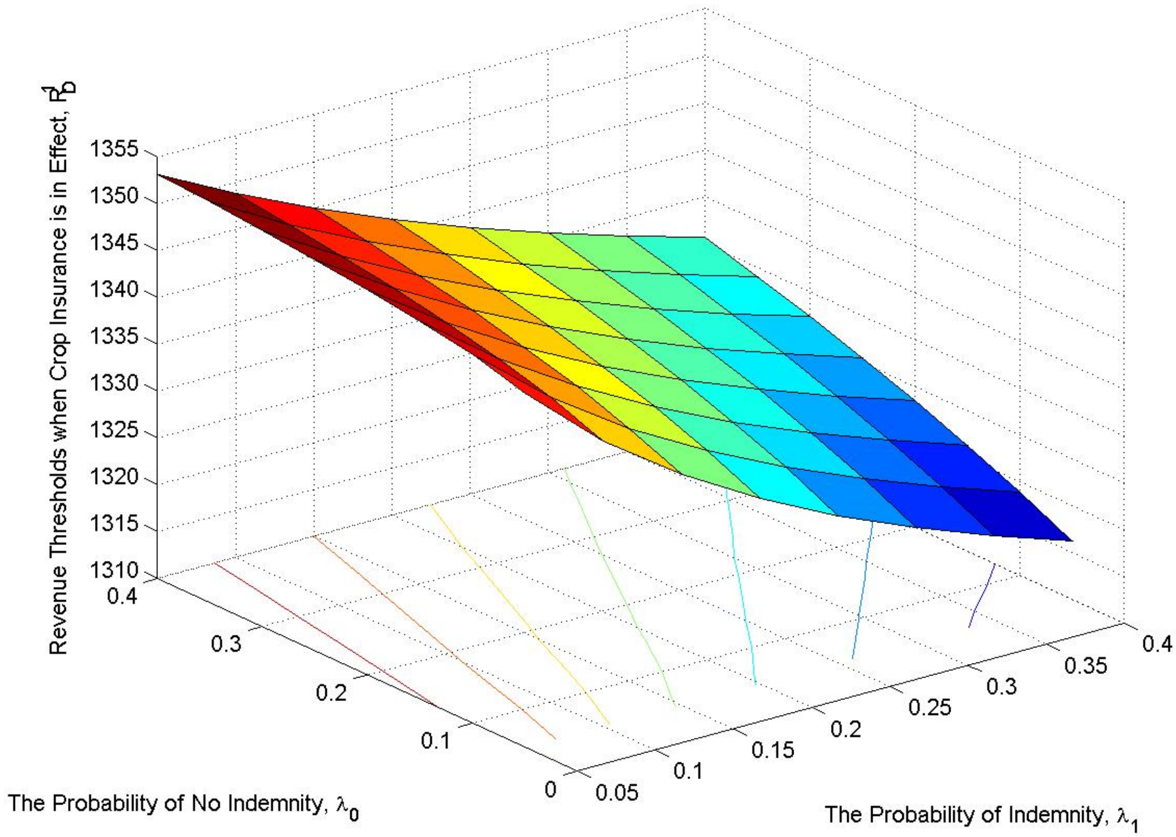

Figure 21. Revenue thresholds when crop insurance is in effect (R_D^1) and $\theta = -30$

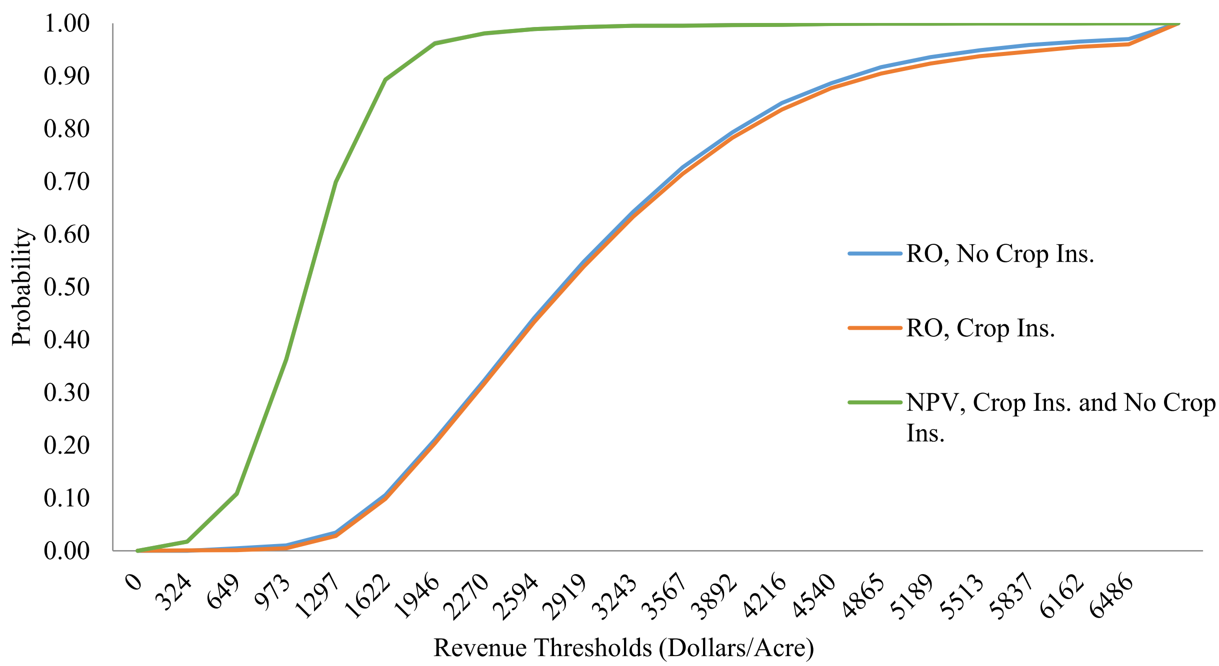

Figure 22. CDF of revenue thresholds

APPENDIX A. DEREVATION OF EQUATION 6A

$V^0(R_D - R_C)= R_D dt - R_C dt + e^{-rdt} E[V^0[R_D - R_C + d(R_D - R_C)]]$.

Applying Ito's Lemma

$V^0(R_D - R_C)= R_D dt - R_C dt + \frac{1}{1+rdt}[V^0(R_D - R_C) + (\alpha_{RD} R_D V_D^0 + \alpha_{RC} R_C V_C^0)dt +$

$½[V_{DD}^0 \sigma_{RD}^2 R_D^2 + 2V_{CD}^0 \rho \sigma_{RD} \sigma_{RC} R_D R_C + V_{CC}^0 \sigma_C^2 R_C^2]dt$.

Rearranging

$$½[V_{DD}^0 \sigma_{RD}^2 R_D^2 + 2V_{CD}^0 \rho \sigma_{RD} \sigma_{RC} R_D R_C + V_{CC}^0 \sigma_{RC}^2 R_C^2] + (\alpha_{RD} R_D V_D^0 + \alpha_{RC} R_C V_C^0) - rV^0 + R_D - R_C = 0 \quad \text{(A1)}$$

The particular solution to (A1) is then

$$V^0(R_D - R_C) = \frac{R_D}{r - \alpha_D} - \frac{R_C}{r - \alpha_C}$$

APPENDIX B. ROOTS OF QUADRATIC EQUATIONS

The quadratic equation associated with range (R_D^0, R_D^1) is

$\frac{1}{2}\sigma^2 \beta(\beta - 1) + (\delta_C - \delta_D)\beta - (\delta_C + \lambda_0) = 0.$

The corresponding characteristic roots, β_1 and β_2, are

$$\beta_1 = \frac{1}{2} - \frac{\delta_C - \delta_D}{\sigma^2} + \sqrt{\left(\frac{\delta_C - \delta_D}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2(\delta_C + \lambda_0)}{\sigma^2}} > 1,$$

$$\beta_2 = \frac{1}{2} - \frac{\delta_C - \delta_D}{\sigma^2} - \sqrt{\left(\frac{\delta_C - \delta_D}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2(\delta_C + \lambda_0)}{\sigma^2}} < 0.$$

The quadratic equations associated with range $(0, R_D^1)$ are

$\frac{1}{2}\sigma^2 \beta(\beta - 1) + (\delta_C - \delta_D)\beta - \delta_C = 0,$

$\frac{1}{2}\sigma^2 \beta(\beta - 1) + (\delta_C - \delta_D)\beta - (\delta_C + \lambda_1 + \lambda_0) = 0.$

The corresponding positive characteristic roots, β_a and β_s, are

$$\beta_1 > \beta_a = \frac{1}{2} - \frac{\delta_C - \delta_D}{\sigma^2} + \sqrt{\left(\frac{\delta_C - \delta_D}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2\delta_C}{\sigma^2}} > 1,$$

$$\beta_s = \frac{1}{2} - \frac{\delta_C - \delta_D}{\sigma^2} + \sqrt{\left(\frac{\delta_C - \delta_D}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2(\delta_C + \lambda_1 + \lambda_0)}{\sigma^2}} > \beta_1.$$