Economics of Oil and Gas Development in the Presence of Reclamation and Bonding Requirements

Yoshiyuki Igarashi[†], Roger Coupal[†], David Finnoff[‡], and Matt Andersen[†]

[†] Department of Agricultural and Applied Economics

University of Wyoming, Laramie, WY 82071, USA

yigarash@uwyo.edu (Igarashi), coupal@uwyo.edu (Coupal), mander60@uwyo.edu (Andersen)

[‡] Department of Economics and Finance

University of Wyoming, Laramie, WY 82071, USA

finnoff@uwyo.edu

Selected Paper prepared for presentation at the Agricultural & Applied Economics Associations 2014 AAEA Annual Meeting, Minneapolis, MN, July 27- 29, 2014.

1 Introduction

Over the last decade the world's appetite for energy and natural resources has grown exponentially, and so has the need for mitigating environmental damage from the resource development. Environmental reclamation and restoration is usually a required part of completing a resource extraction project. The standards of governmental agencies for reclamation vary from agency to agency and level, but often use some kind of bonding scheme to enforce their rules. Environmental bonding related to reclamation has become an increasingly common tool for management of mitigation of natural resource development and impacts. Many industries require bonding to enforce clean up or spill mitigation. Assurance bonding is common in construction, manufacturing, waste management, energy, mining, and more. The motivation for environmental bonding as framed in the literature is a mechanism for providing an incentive for a firm to reclaim disturbances on public lands (Perrings, 1989; Constanza and Perrings, 1990; Gerrard, 2000). Garrard (2000) argues bonding is a market based approach that imposes a cost on the firm for non-compliance, thereby creating an incentive to follow regulatory commitments. It can also transfer the risk of default to a third party.

The use of a bond to manage commitments has advantages, but also limitations. Shogren (1993) identifies three limitations. A moral hazard exists if firms choose to ignore reclamation commitments because they have already internalized the reclamation cost by posting a bond and plan on forfeiting the bond and shirking on the commitment. Liquidity constraints may occur from setting the bond rate too high, thereby tying up investment capital with high opportunity costs. Finally contract failure can occur because reclamation activities are imperfectly enforced due to monitoring issues and legal restrictions (Shogren et al., 1993), as well as simply the long time period between bonding and termination. Natural resource booms and busts are a common and almost expected in resource dependent regions. The current energy boom in Wyoming has resulted in substantially more development than previous booms, and more natural gas driven development. From 1988 to 1998 well counts grew at an annual average rate of 15 percent per year compared to 41 percent per year in the period 1998 to 2008[1]. However, as energy production increases there is growing concern about the pace of development and issues related to the reclamation of disturbed lands.

The purpose of this paper is to evaluate environmental bonding systems operated by State and Federal Agencies as an enforcement mechanism for future remediation. We look at the Bureau of Land Management (BLM) from the perspective of an oil and gas firm. We use a dynamic optimization model to estimate an optimal bond rate for the reclamation of land disturbed by oil and gas development. This study draws from previous work by Andersen and Coupal (2009) that analyzed costs and policies that affect land reclamation decisions by oil and gas firms. We begin by providing a brief description of the current regulatory setting that governs the oil and gas industry in Wyoming and focus our attention on reclamation bonding requirements, which are intended to insure the proper reclamation of disturbed land. The most important issue affecting the decision to reclaim is the cost of reclaiming the disturbed land (although other factors such a clear reclamation guidelines and standards set by

[1]Calculated from Wyoming Oil and Gas Conservation Commission data

land management agencies are important as well). We then empirically test this analysis by constructing an dynamic optimization model in GAMS with empirically derived parameters to calculate an optimal bond per well.

As of 2009, there were more than 68,000 active oil and gas wells in the state operated by approximately 900 separate firms. The number of gas producing wells peaked at 28,969 wells in 2008. In 2012 the number of gas producing wells dropped to 22,171 as the price of natural gas dropped according to the data of Energy Information Administration (EIA). This level of activity suggests that reclamation issues will become more important in the future as production in these wells ends and are plugged and released or abandoned. Factors that become important in successful reclamation include the regulatory environment, industry structure, and environmental factors associated with the specific location of the field or well. Given the sheer number of wells and their distribution across varying ecological and precipitation regimes, as well as the sharp increase in development over the past decade, the structure and expectations of reclamation regulations becomes an important policy issue for State and Federal Agencies.

The two primary regulations that provide the regulatory basis for reclamation in oil and gas development are the Stock Raising Homestead Act of 1916 (SRHA) and Mineral Leasing Act (MLA). SHRA allowed non-surface owners access to subsurface mineral rights because the rights were held by the Federal government. The Act required that companies compensate surface owners for loss of use at a fair market agricultural level. Amendments to the Act in the latter half of the 20th century required these compensations to surface owners be in the form of a bond. MLA introduced the bond to ensure compliance with all the lease terms, which includes protection of environment. The BLM policy on bonding in Wyoming allows firms to choose from three options for the right to extract: 1) pay a single-site lease fee of $10,000; 2) pay a blanket bond of $25,000 for all the wells they drill in the state; or 3) post a blanket bond of $150,000 that covers all wells in the entire nation[2].

The environmental bond is designed to provide an incentive to perform land reclamation instead of walking away (Perrings, 1989). The higher the bond the higher is the incentive to retrieve the posted bond. However, firms can face liquidity constraints because bond is not a liquid asset (Shogren et al., 1993) and small and medium-sized firms that have limited access to credit will face an opportunity cost in the use of those funds (Davis, 2014). Even if the size of the bond posted by firms enough to cover reclamation costs based upon current estimates the size of bond posted in the initial period is not guaranteed to satisfy the required amount of final reclamation cost in the terminal period which can be decades later.

The form of payment for environmental bonds differs between federal and state levels of government. Federal leases can be one of several forms: A cash bond paid for by a direct transfer of funds, a letter of credit on operations, a lien on equipment, or a surety bond. Oil and gas operations that occur on State or privately owned land are regulated by the Wyoming Oil and Gas Conservation Commission and the Wyoming Department of Environmental Quality. These bonds are cash bonds. See Andersen, et al (2009) for a more discussion on the alternative forms of bonds.

Limitations aside, there are reasons why firms do complete reclamation commit-

[2]On a per well basis firms need to pay $10,000 for one lease by the federal surface lease requirement (WORC, 2004)

ments. Sult (2004) developed a model of reclamation decision making for coal mines incorporating fines for non-compliance and reputation costs. The model predicted that reclamation depends upon the entire cost of reclamation, including fines and increased management cost from a change in reputation in the eyes of the regulators. In general reputation effects can insure reclamation activities are completed even in the presence of a small bond that does not fully cover costs (Gerard, 2000). Firms will complete reclamation activities simply to avoid potential business losses because of a damaged reputation, which can affect a company's relationship with regulators, increasing operation costs. A damaged reputation can also affect a company's relationship with consumers, potentially decreasing revenues.

The BLM's current environmental bonding system suffers from two design flaws: the failure to properly account for time value of money given that bonds are posted in the beginning of the production process, but reclamation is completed after the well is capped and the bond level is not tied to production (Andersen and Coupal, 2009). Operators do not receive interest on cash bonds and given the long life a typical oil and gas well operators incur a substantial opportunity cost of capital as the initial value is largely forfeited over the life of the operating well.

A broad-based blanket bond is also inefficient because it is not linked to production. Webber (1985) argues that the amount of fee, deposit, tax, or bond should vary due to several factors, such as a well location, production technique employed, and the amount of oil or gas produced. The blanket bonds and other current bonding requirements result in bonding amounts that are insufficient to cover the full cost of reclamation as a producer increases the number of operating wells. For example, data on the cost of reclaiming 255 orphaned wells in the state of Wyoming from 1997-2007 showed that bond levels were as low as 20 of the actual cost (Table 1). These cost figures represent the actual costs incurred by contractors for the WOGCC in the process of fully reclaiming a total of 48 separate locations on state fee lands. Table 1 shows the actual cost, bond amount, and variance (difference between cost and bond) for the full set of 255 wells: 1) per foot of drilling depth; and 2) per well.

Table 1: Orphaned Oil & Gas Wells in Wyoming (1997-2007)

	Actual Cost	Bond	Variance
Per foot of drill depth	$10.81	$1.79	$9.02
per well	$29,136	$5,989	$23,147

While the actual cost of the full reclamation of the 255 wells averaged $10.81 per foot of well depth, and approximately $29,136 per well, the bond per foot of well depth was $1.79 and per well was $5,589 respectively. Part of the reason why the bond amount per foot of well depth and per well seems low is because the full sample includes some wells that had no bond posted, as their development likely pre-dated the bonding regulations. However, this gives a good indication of the variance that likely currently exists in Wyoming because there is a mix of older wells with no bond posted, and newer wells that are fully bonded. The existence of the older un-reclaimed wells with no bond places an added financial burden on the state, above and beyond insuring that funds are available in the future to reclaim current development.

As shown in Table 1, the posted bond is considerably smaller than the actual costs. This discrepancy between actual costs and posted bond suggests that the current bonding system is not a viable deterrence to walking away from reclamation obligations. If the bond is set too low and the company reneges on its commitment, the state could get stuck with the bill for the reclamation. On the other hand, if the bond rate is set too high it can have an adverse effect on the industry and a sub-optimal outcome. The optimal bond rate will be determined by a proper accounting of the time dimension of this problem, and incorporation of planned reclamation costs. In order to estimate the optimal bond rate we construct a dynamic optimization model of an oil and gas firm that incorporates the bond and opportunity cost of capital.

Because of the limitations of environmental bonding as a 'pure' incentive as discussed above, the US Bureau of Land Management shifted to what they call an 'operated-acreage basis' approach or what we define as a maximum allowable disturbed acreage (MADA) added to the current bonding structure (BLM, 2006). The agency calls this rule a "rollover cap". For this analysis we assume MADA and rolling cap are synonymous.The point of MADA policies is that a firm has to do a sufficient amount reclamation on currently disturbed lands to qualify for developing wells in other areas. Attached to this cap on disturbance are rules that provide metrics for which to complete reclamation and restoration in a timely manner at a level required by the agency. Successful reclamation is defined in the Oil and Gas Gold Book (BLM, 2007, p. 43) as " With proper reclamation measures, over time, local native species will become re-established on the site and the area will regain its original productive and scenic potential". More detailed or specific metrics are established at the local Field Office level that accounts for past behavior of firms and specific ecological and environmental characteristics of the area. These include soil erosion and vegetative goals, and interim reclamation requirements. The original use of the rollover criteria was used in the Continental Divide - Creston Gas Project in South Central Wyoming (BLM 2011). It is the latter, interim reclamation, coupled with MADA and the environmental bond are what we evaluate in this paper. It is important to note that the specific rule surrounding MADA came from an interpretation of existing rules covered in the Gold Book. The book itself does not actually bring up the notion of MADA. This concept is being formally used in some areas of the Rocky Mountain has been a consideration and an informal metric in other areas.

Increasingly, as part of the reclamation plan industry is required to do both interim and final reclamation. Interim reclamation occurs after development of the site is completed and disturbed areas that are not needed for production maintenance but use in the development process are reclaimed (BLM 2007). Since a well can last for years reclamation and restoration in the interim reduces the potential threat of invasive and noxious weed establishment. It also begins the process of returning to the orignial ecosystem. (Another motivation, not stated in regulatory reports, is that due to decline curve patterns in most wells, where production is at its maximum just after well completion and then declines, industry is at its most financially flexible early in the process).

A third financial instrument used is a mill levy on the value of oil and gas mined and marketed. The proceeds of this levy go into a Abandoned Well fund that goes to pay for reclamation when a firm does not complete reclamation and restoration, but “walks away”. As prices for natural gas declined due to development of shale gas plays or shale oil plays coupled with gas, "dry" gas wells (solely methane) became unprofitable. As of the end of 2013 Wyoming had 1,200 wells on private or state land where the operator went bankrupt or walked away plus another 2,300 wells idled and likely to be abandoned, and another 400 on federal land. The mill levy that collected these funds was not sufficient to cover all the abandoned nor expected abandoned wells (NYT, 2013). We evaluate the mill levy approach compared to bonding, with only final reclamation and interim reclamation.

2 Analytical Framework and Model

We develop a discrete time framework in the spirit of Pindyck's (1978) continuous time model of exploration and production, similar to Deacon (1993). Pindyck (1978) considers the behavior of a firm maximizing net present value (NPV) by controlling discovery and production, endogenizing the reserve process. Deacon (1993) applied Pindyck's principles in a discrete time setting, meshing the modeling environment with with observed data. We extend the principles of these models by including reclamation policies and their costs structures specific to natural gas development and production. We build a general model of oil and gas development without reclamation policies. We in reclamation requirements, both interim and final reclamation strategies, a model with a fixed bond, and a model with a mill levy.

Discrete Time Model without Reclamation Policies

The representative firm operates in a perfectly competitive market, obtaining revenue by producing and selling natural gas, and paying the expenses of producing natural gas and drilling wells. Current profit without reclamation is represented as

$$\pi_t = p_t q_t - C_P\left(q_t, R_t\right) - C_D\left(w_t\right). \tag{1}$$

Let p denote price of natural gas, q denote production, R denote proved reserve and w denote drilling effort which includes the surface activity for exploration and development of wells. The exploration and drilling effort is measured by the depth of newly drilled wells. The functions $C_P(\cdot)$ and $C_D(\cdot)$ denote production and drilling cost. We assume that the price is exogenously determined and parameterize it with a logistic function, $g(t)$. The logistic price function is calibrated in the following section.

The reserve addition at period t is

$$R_t = R_{t-1} + F(X_t) - F(X_{t-1}) - q_{t-1}, \tag{2}$$

where X is cumulative depth of wells and $F(\cdot)$ is a function representing cumulative discovery. Net change of cumulative discovery between any two periods, $F(X_t) - F(X_{t-1})$, represents the current discovery at t in equation (2). Similarly, the change in cumulative depth is represented as

$$X_t = X_{t-1} + w_{t-1}. \tag{3}$$

We combine the objective function (1) with the difference equations (2) and (3). The discrete-time profit maximization model without a reclamation requirement is

$$\max_{q_t,w_t}\Pi = \sum_{t=1}^{T}\beta^{(t-1)}[p_tq_t - C_P(q_t,R_t) - C_D(w_t)]$$

$$\text{s.t.}$$

$$R_{t+1} = R_t + F(X_{t+1}) - F(X_t) - q_t,$$

$$X_{t+1} = X_t + w_t, \tag{4}$$

$$p_t = g(t),$$

$$q_t \geq 0, w_t \geq 0, R_t \geq 0, X_t \geq 0,$$

$$R_0\ , X_0 \text{ given}, R_T\ , X_T \text{ free},$$

$$q_T = 0, w_T = 0.$$

The boundary conditions, $q_T = 0$ and $w_T = 0$, set both of the control variables to zero because we assume the firm ends operations at the terminal period. β is the discount factor. In contrast to the control variables, no boundary condition is set on the state variables as the constraint in (4), which shows R_T and X_T are free variables.

The present value Lagrangian expression for the problem is:

$$L = \sum_{t=1}^{T}\beta^{t-1}\left\{\begin{array}{l} p_tq_t - C_P\left(q_t,R_t\right) - C_D(w_t) + \beta\lambda_{t+1}^{R}\left[R_t + F(X_{t+1}) - F(X_t) - q_t - R_{t+1}\right] \\ +\,\beta\lambda_{t+1}^{X}\left[X_t + w_t - X_{t+1}\right] \end{array}\right\} \tag{5}$$

where $p_t = g_t$ is taken as given, and all the boundary conditions follow from the main text. The key variables introduced by the optimization procedure are the costate variables given by λ^i_{t+1}. They can be interpreted as the (shadow) value of an additional unit of each state variable $i = (R, X)$ in period $t + 1$. They provide a signal to the decision maker in period t of the opportunity costs / gains of drilling and production, and values of changes in the states.

Optimization proceeds by finding optimality conditions with respect to free variables w_t, q_t, R_t, X_t and λ^i_{t+1}. In what follows additional subscripts indicate partial derivatives.

For all w_t:

$$\frac{\partial L}{\partial w_t} = -C_{D,w_t}(w_t) + \beta\lambda^X_{t+1} = 0, \tag{6}$$

For all q_t:

$$\frac{\partial L}{\partial q_t} = p_t - C_{P,q_t}(q_t, R_t) - \beta\lambda^R_{t+1} = 0, \tag{7}$$

For all R_t:

$$\frac{\partial L}{\partial R_t} = -C_{P,R_t}(q_t, R_t) + \beta\lambda^R_{t+1} - \lambda^R_t = 0, \tag{8}$$

For all X_t:

$$\frac{\partial L}{\partial X_t} = -\lambda^R_t F_{X_t}(X_t) - \lambda^X_t + \beta(\lambda^X_{t+1} - \lambda^R_{t+1} F_{X_t}(X_t)) = 0, \tag{9}$$

For all λ^R_{t+1}:

$$\frac{\partial L}{\partial \lambda^R_{t+1}} = R_t + F(X_{t+1}) - F(X_t) - q_t - R_{t+1} = 0, \tag{10}$$

For all λ^X_{t+1}:

$$\frac{\partial L}{\partial w_t} = X_t + w_t - X_{t+1} = 0, \tag{11}$$

Boundary conditions:

$$q_T = 0, w_T = 0. \tag{12}$$

The optimality condition (6) requires drilling effort to be expanded until the marginal cost of drilling in the current period, just equals the discounted marginal benefit of drilling, the shadow value of cumulative depth in the next period.

Gas is produced following condition (7) up to the point where current marginal revenue of production equals the sum of current marginal costs of production and the opportunity costs of production. The opportunity costs of production are the discounted forgone future benefits that a larger reserve in $(t + 1)$ would generate. Equation (8) provides the value of an additional unit of reserves under an optimal plan:

$$\lambda^R_t = \beta\lambda^R_{t+1} - C_{P,R_t}(q_t, R_t). \tag{13}$$

Current reserves have value through their contribution to future reserves and their ability to reduce marginal costs in the current period. Similarly, the value of additional cumulative depth from Equation (9) is:

$$\lambda_t^X = (\lambda_t^R - \beta\lambda_{t+1}^R)F_{X_t}(X_t) + \beta\lambda_{t+1}^X. \tag{14}$$

An additional current unit of cumulative depth generates value through its marginal contribution to current reserves, net of the discounted loss in value in future reserves (as cumulative changes in depth matter to reserves), and from the discounted value of an additional unit of cumulative depth in the next period.

Equations (10) and (11) require the system dynamics to follow the given laws of motion. The equations of optimality must be simultaneously solved over all time periods given the initial conditions on the state variables and the terminal conditions on the control variables. Little insight can be garnered analytically about optimal choices overtime. In what follows we focus on a numerical implementation of the model in GAMS.

Discrete Time Model with Reclamation and Tax Policies

We consider two variants of reclamation policies - interim and final, both with a reclamation bond under MADA. The point of MADA policies is that a firm has to do a sufficient amount reclamation on currently disturbed lands to qualify for developing wells in other areas. This concept is being formally used in some areas of the Rocky Mountain has been a consideration and an informal metric in other areas.

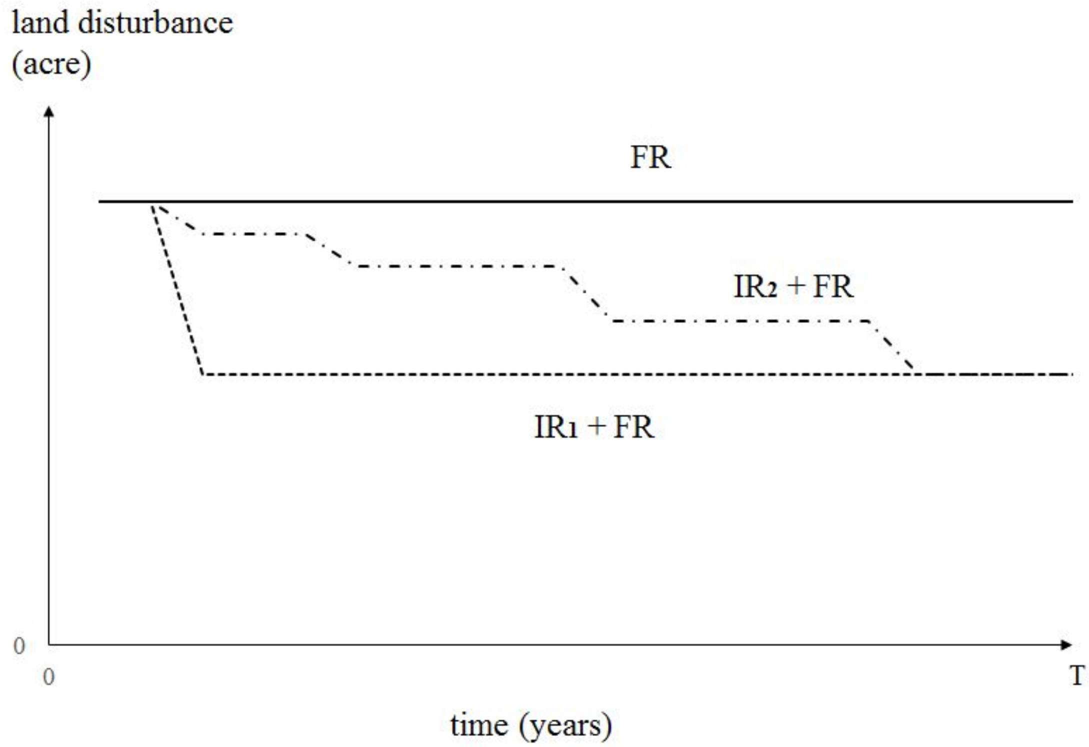

Figure 1: Change of land disturbance by interim reclamation

The firm has a choice to reclaim as much as it is able without significantly affecting production, or the firm can wait and finish it after wells are capped as Figure 1 shows. In our model, we assume that final reclamation must be performed by the firm to reclaim the entire disturbed area through the development and production activities at the terminal period, T. On the other hand, the firm is able to choose the timing and the size to perform interim reclamation at every period until one period before the terminal period, which is $(T-1)$. The firm can clean up the unnecessary land for the use of production right after the initial development, such as IR_1, or the firm can gradually perform the interim reclamation, such as IR_2.

The size of area performed interim reclamation at t is denoted as y_t, and this interim reclamation effort is a control variable, which is measured in acre. The total size of land disturbance at t is denoted by S_t, which is measured in acre, and the difference equation is represented as

$$S_t = S_{t-1} + \eta w_{t-1} - y_{t-1} \tag{15}$$

The parameter η converts the depth of wells to the size of land disturbance because land disturbance (acre) and exploration and drilling effort (thousand feet) have different units. This conversion rate is calculated based on the average initial size of well pads in Wyoming and the average depth per well in Wyoming.

The model incorporates a generalized framework for reclamation where reclamation can be accomplished during the production process and completed after the well is capped. The second term in (15) reflects that the total land disturbance increases as development increases. We assume that the size of disturbance is positively related to exploration effort and damages to the environment around field are homogenous across the area. MADA limits continued potential development until reclamation is completed based upon regulatory guidelines.

We introduce into the model two more variables: Reclamation costs and an orphan well mill levy. Reclamation costs where interim occurs just after well completion and final occurs after capping the well at the terminal period (4). interim reclamation enters into the model as a control variable and the total size of land disturbance as a state variable; thus, the new model has three control variables and three state variables. Also, new constraints are introduced to reflect the reclamation policies and bonding structure. The model with reclamation and tax policies is represented (7).

$$\begin{aligned}
&\max_{q_t,w_t,y_t} \Pi = \sum_{t=1}^{T} \beta^t[(1-\tau)\, p_t q_t - C_P(q_t, R_t) - C_D(w_t) - C_{IR}(y_t)] - \beta^T C_{FR}(S_T) \\
&- \left(1-\beta^T\right) B_0 \\
&\text{s.t.} \\
&R_{t+1} = R_t + F(X_{t+1}) - F(X_t) - q, \\
&X_{t+1} = X_t + w_t, \\
&S_{t+1} = S_t + \eta w_t - y_t, \\
&p_t = g(t), \\
&S_t \leq \bar{S} \\
&q_t \geq 0, w_t \geq 0, y_t \geq 0, R_t \geq 0, X_t \geq 0, S_t \geq 0, \\
&R_0\ , X_0\ , S_0 \text{ given}, R_T\ , X_T \text{ free}, \\
&q_T = 0, w_T = 0, S_T = 0.
\end{aligned} \tag{16}$$

The model maximizes the NPV of net revenues for a representative firm incorporating reclamation costs, interim C_{IR} and final C_{FR}, the bond B_0, a mill levy τ that contributes to an orphan well fund for cases where a firm does not follow through on its reclamation obligation but "walks away" and the agency has top complete the work. The firm posts the reclamation bond in time zero and retrieves bond at the terminal period, T. The firm complies with reclamation regulations which limits the total size of disturbed area until most is reclaimed. The firm can perform interim reclamation to continue development because of MADA constraint $S_t \leq \bar{S}$. This model incorporates the reclamation bond as the firm posts at the initial period, and the bond is retrieved at the terminal period. The cash flow specifically on the bond is $(\beta^T - 1)B_0$, and the firm increases the loss as the terminal period is postponed, because the discounting factor, β, reduces the real value of retrieved bond. The models are numerically solved using GAMS with MINOS and IPOPT developed by Wächter and Biegler (2006).

3 Data Sources and Estimation

The empirical model requires estimation of four functions, which are production total cost, drilling cost, cumulative discovery function and reclamation cost. We estimate these functions using data from the Wyoming Oil and Gas Conservation Commission (WOGCC) and the U.S. Energy Information Administration (EIA). All prices and costs used for the estimation are in real 2005 dollars adjusted using the GDP implicit price deflator.

Production Costs

The data on production cost is collected from oil and gas lease equipment and operating costs from 1989 to 2009. We use the data on operating cost of the producing wells in the Rocky Mountain area and the depth of wells is 4 thousand feet. The production cost includes production measured and proved reserves. The units of these variables are million cubic feet (MMcf), and the unit of production cost is million dollars. The production cost non-linearly increases as production increases. The production cost decreases as proved reserves increases because it is assumed that the representative firm can choose a site easier to produce when the firm has abundant reserves. Based on this inversely proportional assumption on reserve, the log linear form of the restricted regression model is:

$$\begin{aligned} \ln C_P\left(q, R\right) &= -\,13.193 \quad +3.032q \quad -\ln R \\ & \quad\;\; (-5.65) \qquad (18.26) \end{aligned} \tag{17}$$

where R are available reserves, q is production, α are estimated parameters.

Drilling Costs

The drilling cost is measured in million dollars as well as the production cost. The drilling cost per million feet is represented by the function of the depth of wells:

$$\begin{aligned} \frac{C_D(w)}{w} &= 35.639 \quad +0.000167w \\ & \quad (2.70) \qquad (10.38) \end{aligned} \tag{18}$$

A quadratic form was chosen to account for a perceived exponential relationship with drilling depth.

Cumulative Discovery Function

The new discovery in the current year is calculated by the difference of cumulative discovery between two periods. The function for the cumulative discovery is assumed to be strictly increasing and concave. The amount of cumulative discovery increases in response to the cumulative drilled depth. The cumulative discovery function is estimated by the second order polynomial approximation, and it represented by the following regression model:

$$\begin{aligned} F(X_t) \; &= 11885001 \quad +62.114X_t \quad -0.00001572X_t^2 \\ &\quad\;\; (16.15) \qquad\quad (17.55) \qquad\quad (-5.72) \end{aligned} \tag{19}$$

Reclamation Costs

Reclamation costs are modeled as a function of well depth. As indicated in Table 1 from Andersen, et al (2009) over 80 percent of reclamation costs are associated with issues related to to the hole. Data from the Wyoming Oil and Gas Conservation Commission are used in the regression. The databases has detailed information on well depth, production, and products being produced. We add specific information from the WOGCC and the BLM orphan well data, where firms neglected to do the required reclamation but instead ”walked away”. Cost data then come from contracted costs to finish reclamation on orphaned wells. For more information see Andersen, et al (2009). Costs are assumed to be linear since other functional forms did not perform as well.

$$\begin{aligned} RC(w) = \quad & 5.8w \\ & (10.16) \end{aligned} \tag{20}$$

4 Results

The average depth of well among the orphaned wells is 4,602 feet per well. The real well head price of natural gas in Wyoming per million cubic feet (MMcf) in 1989 was $1,780. The initial price of simulations is $1,780 per MMcf. We model prices using a logistic functional form where the price eventually reaches $3.38 which is an average price of natural gas from 1989 to 2010 in real value. The calibrated logistic price function is

$$p_t = 0.191 + \frac{3.186}{1 + 1.6^{(-t+1)}}. \tag{21}$$

Discrete Time Model without Reclamation Policies

The discrete model without reclamation is represented in (4). Units of production and proved reserves are measured in mcf, and the unit of drilling effort is measured in thousand feet. The length of the simulation is 32 years. The annual growth rate of NPV becomes one percent when the terminal period is set to 32. The paths for production, drilling effort and assumed price paths without reclamation are shown in Figure 2.

In our result we have the price peak at $3.8 in Year 17 and then levels out. Production peaks in Year 13, drilling peaks in Year 2 and reserves peak in Year 3. Proved reserves diminish over periods, but the firm does not exploit entire reserve because state variables are free at the terminal period. The firm leaves some proved reserves underground to make cash flow zero at the terminal period. If the firm produces more and reduces reserves, the cash flow at the terminal period becomes

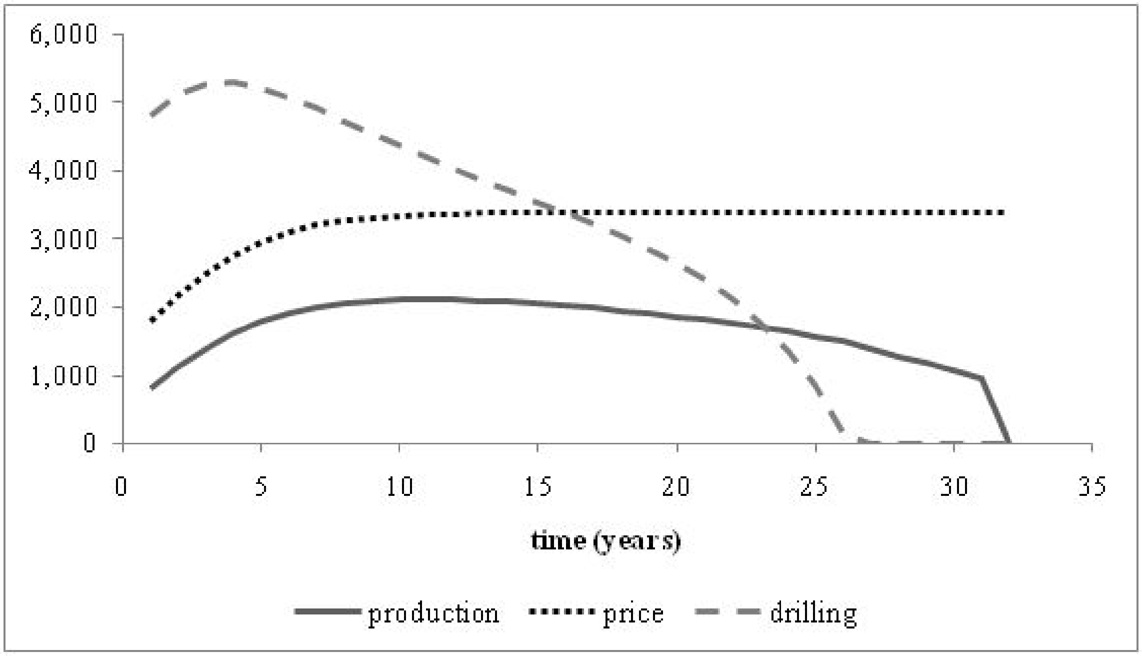

Figure 2: Paths for production (MMcf $\times 10^3$), price(\$ $\times 10^3$) and drilling (feet $\times 10^3$)

negative because of the estimated production cost function; however, the reserves will run out if the terminal period is set longer. Because the estimated production cost function is convex in production, the firm cannot produce all of the leftover within a short period. The drilling reaches zero in Year 15 because the firm has enough reserve to stay along the optimal paths. If the firm starts operation with the small amount of initial reserve, the drilling effort will continue until Year $(T - 1)$ based upon the boundary conditions in our model.

Discrete Time Model with Reclamation and Tax policies

The reclamation policies include final reclamation, interim reclamation, MADA and a current environmental bonding system in Wyoming. We assume the representative firm chooses \$25,000 of blanket bond which covers all drilled wells in Wyoming.

In addition to these policies related to reclamation, the firm incurs of mill-levy tax for the orphan well fund. The average mill levy on oil and natural gas in Wyoming is 6.2% (USDI, 2012). Our model adopts this mill levy rate for simulation. The discrete time dynamic optimization model with reclamation policies is represented in (21).

The terminal period of the simulation is determined when the annual growth of NPV decreases to a certain threshold, which is one percent in our model. Figure 3 shows the paths for production, drilling effort and assumed price path with reclamation and tax policies. Buto et al. (2010) investigated the average initial pad size in Wyoming is 4.10 acres per well. We calculate the conversion rate between drilling

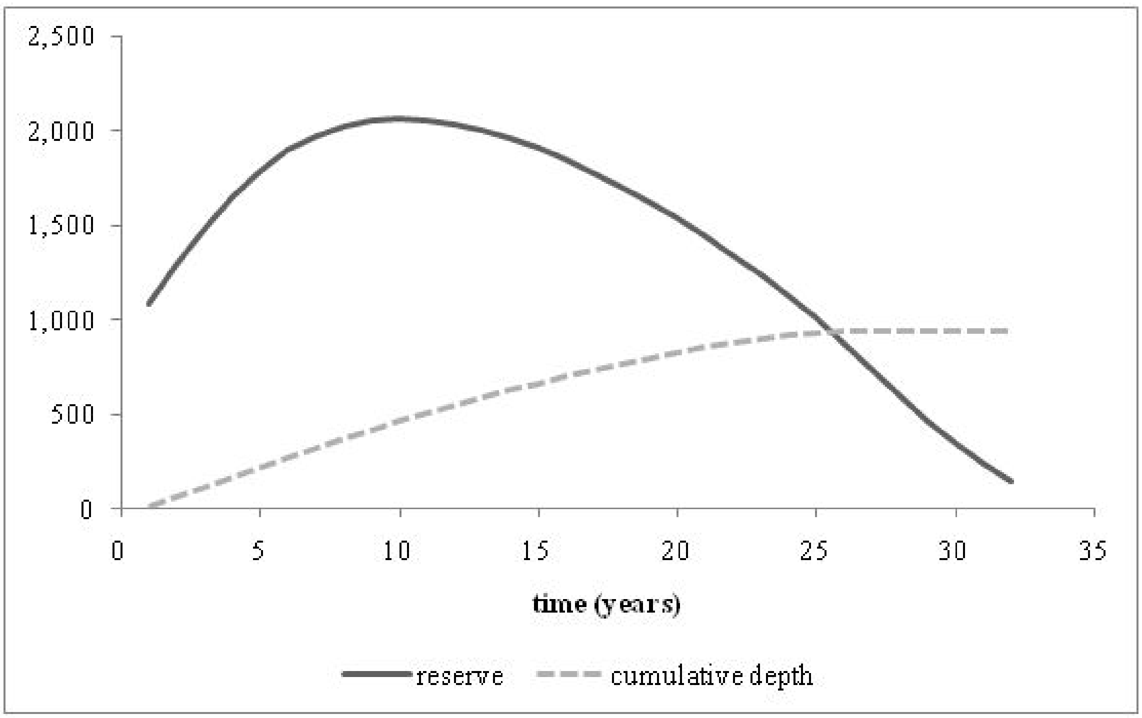

Figure 3: Paths for reserve (MMcf $\times 10^3$) and cumulative drilling (feet $\times 10^6$)

effort measured in thousand feet and disturbed area measured in acres. Because the average depth per well in Wyoming is 4,602 feet and the size of well pad is 4.10 acres, the size of disturbed area per thousand feet of depth is 0.891 acres. The unit for the state equation for total land disturbance is standardized in acres, and the difference equation for the total land disturbance is represented as

$$S_{t+1} = S_t + 0.891w_t - y_t \tag{22}$$

The simulation assumes an average well pad size for Wyoming of 2.8 acres per well. We estimate an appropriate size of MADA to run simulation based upon average size of well pad in Wyoming. The number of producing gas wells in the State peaked in 2006, with 28,969 wells. Because the lifetime average pad size in Wyoming is 2.80 acre per well, the total size of area necessary for production in Wyoming is 81,113.2 acre. The following simulations set this number as the limit of MADA, which is $\bar{S} = 81,113.2$ in the model (16). As well as the simulation result without reclamation, the peak of the production is in Year 11, and drilling peaks in Year 4 as Figure 4 shows. Drilling reaches zero in Year 26, and this is one period earlier than that without reclamation policies.

We contrast two simulation results with and without reclamation policies. When we contrast the simulation results with and without reclamation and tax policies, the results with reclamation policies shows that total production drops 9.8%,total drilling effort drops 16.9%, reserve drops 11.7%, and NPV drops 4.3%. Drilling effort drops most because drilling directly increases interim reclamation and final reclamation cost. In response to the large percent of reduction in drilling, proved reserves do

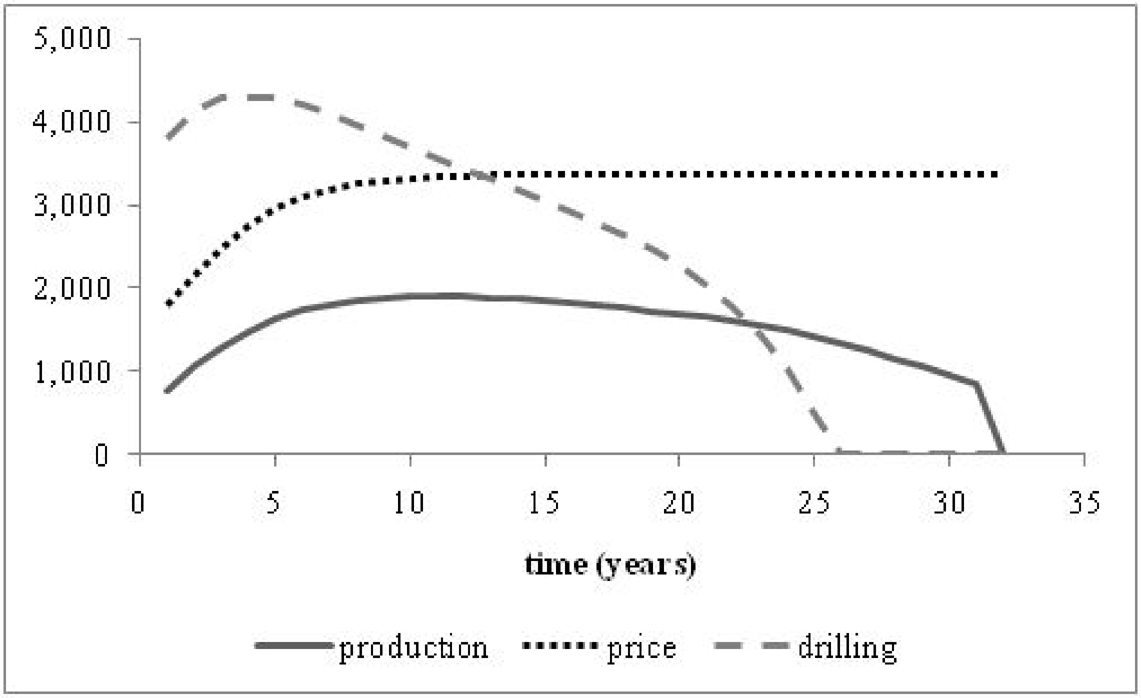

Figure 4: Paths for production (MMcf $\times 10^3$), price($\$ \times 10^2$) and drilling (feet $\times 10^4$)

not decrease much because of the concavity of the estimated discovery function.As a sequence of cause and effect, NPV drops only 4.3% because of the relatively small drop in production.

As Figure 5 shows, total land disturbance binds MADA in Year 10. The firm performs interim reclamation from Year 9, and stops performing interim reclamation in Year 14 because drilling effort ceases in the same year. The firm discontinues interim reclamation and stays on MADA because the firm is able to discount the total reclamation costs by postponing until the terminal period and just waits to perform final reclamation. If the discount rate is zero, the firm is indifferent from continuing interim reclamation after Year 14.

The sum of discounted interim reclamation cost is \$2,080,102 and the discounted final reclamation cost is \$211,097. The total interim reclamation cost becomes greater than the final reclamation cost because of the effect of MADA. If MADA is not imposed, the representative firm's incentive is to defray the entire reclamation cost to the terminal period. So the combination of interim reclamation and MADA motivates the firm to do the reclamation and incur costs annually throughout the firm's production activities.The discounted total reclamation cost is \$2,291,198 and NPV is \$42,718,420.Thus, the discounted total reclamation cost occupies 5.4% of NPV.

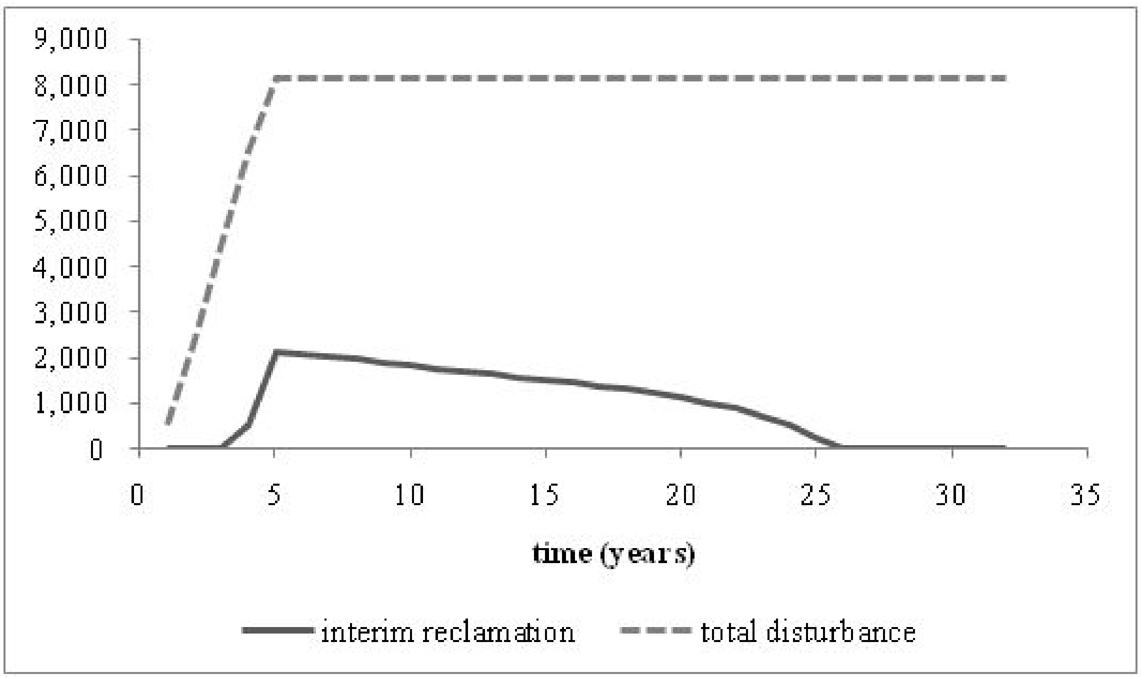

Figure 5: Paths for interim reclamation (acre $\times$ 10) and total land disturbance (feet $\times$ 10)

5 Sensitivity Analysis

Discovery Functions with Different Functional Forms

We estimate a simple discovery function for natural gas that follows Pindyck (1978) and Deacon (1993) where cumulative depth, X, is a function of net discovery. Discovery in this sense is not new simply new fields or formations, but also includes increases production from techniques to expand production on existing fields. So it is a generalized definition of discovery. We show the simulation results produced by different forms of estimated and calibrated discovery functions. We use the cumulative depth of wells as independent variable because cumulative depth is able to explain the depletion of potential stock of natural gas underground. We have three different forms of discovery functions, such as polynomial, natural log and logistic form. The natural log discovery function is concave to the cumulative depth. The discovery function in natural log form with an intercept is represented as:

$$\begin{aligned} F(X_t) \quad &= -\ 118984027 \quad +12342930 \ln X_t \\ &\quad\ (-8.30) \qquad\qquad (10.63) \end{aligned} \tag{23}$$

Next, the calibrated logistic discovery function is calibrated based on the data on cumulative depth. The calibrated logistic discovery function is also concave to cumulative depth. The discovery function is represented as:

$$F(X_t) = 7.5 \times 10^7 \left(1 - e^{-0.0000015 X_t}\right) \tag{24}$$

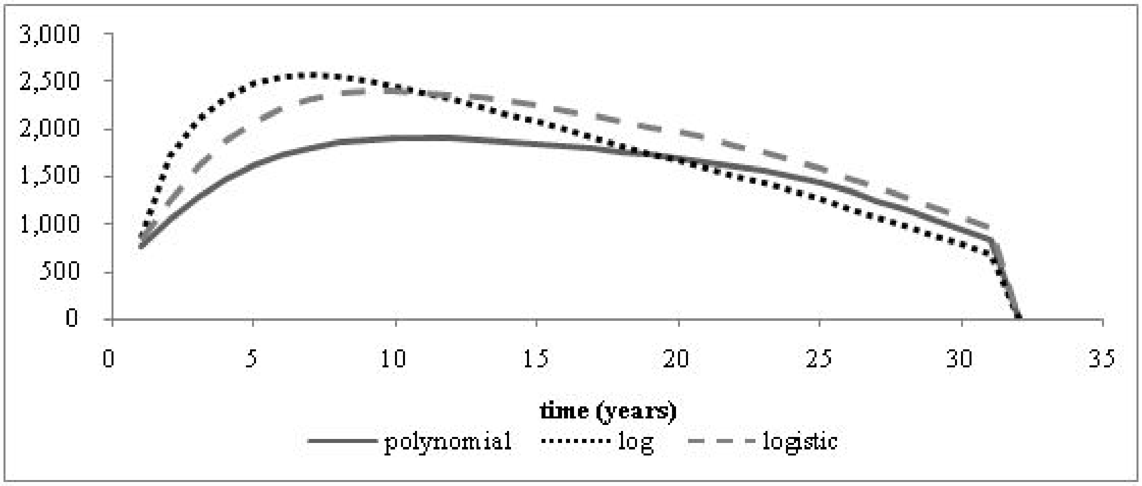

Figure 6: Paths for production from different discovery functions (MMcf $\times 10^3$)

We will demonstrate the effects of the functional forms and parameters by showing the paths of variables from different discovery functions. We set the terminal period to Year 32 to compare and contrast the trajectories of variables[3]he growth rate of NPV with natural log discovery function reaches 1 percent of the growth rate in Year 27, and the growth rate of NPV reaches in Year 30. Figure 6 shows that the natural log discovery function produces most at the beginning; however, the models with polynomial and logistic discovery functions produce more than the model with natural log discovery function around the terminal period.

The differences in the trajectories of production are explained by the paths of current discoveries in Figure 7. Current discovery under a natural log structure generates generates more discovered resources than from other cumulative discovery function structures, but then exhibits decreasing rates which causes a drop in production. As well as the trajectories of production, the differences in functional forms

[3]T

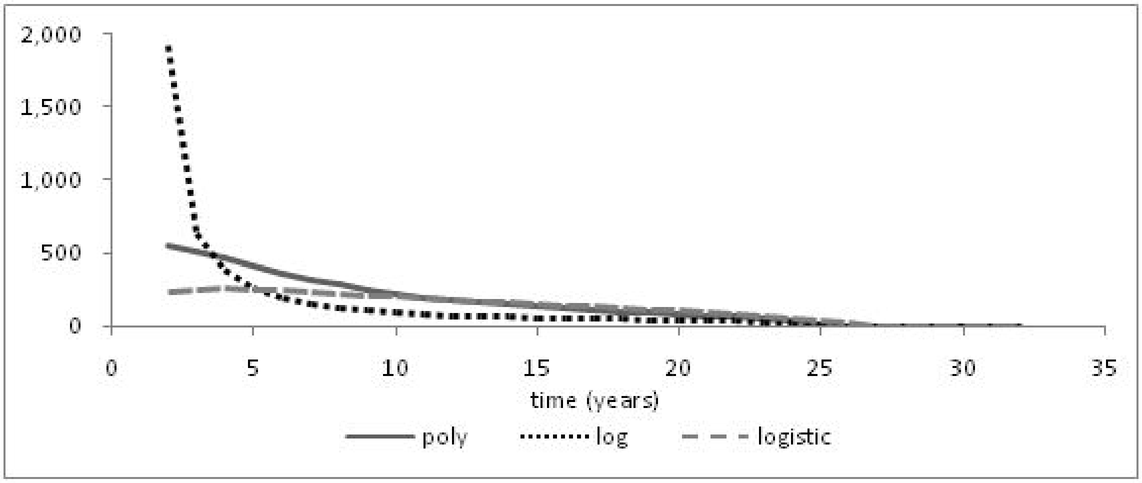

Figure 7: Paths for current discoveries from different discovery functions (MMcf $\times 10^4$)

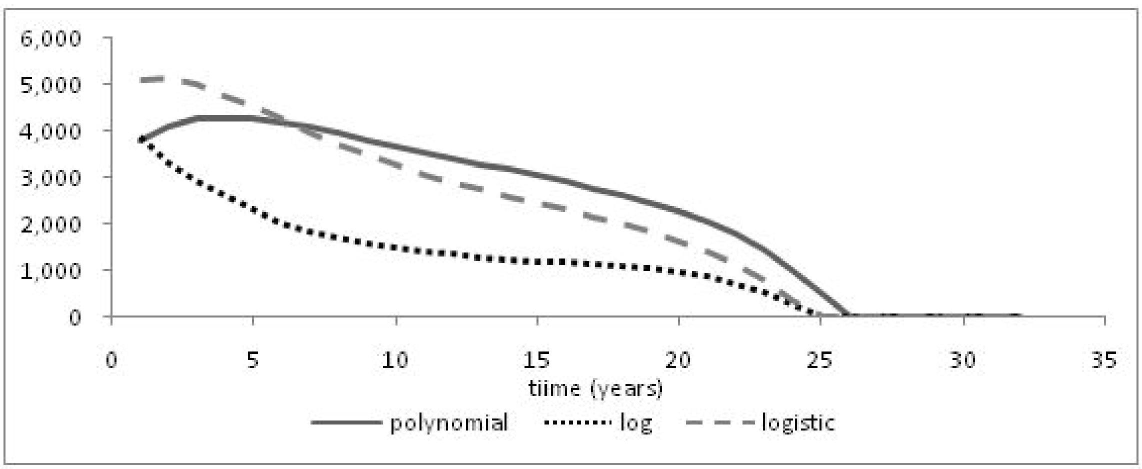

Figure 8: Paths for drilling from different discovery functions (feet $\times 10^4$)

influence the trajectories of drilling in Figure 8. The sharp reduction in current discovery from the natural log cumulative discovery function leads to a declining path of drilling because increase in cumulative depth of log cumulative discovery function is not as effective as other cumulative discovery functions.

Simulation Results with Different Terminal Period

We set the terminal period for our simulations at a time when the annual growth rate of NPV is less than one percent. We demonstrate the effects of extending the terminal period to NPV. The setting of this simulation has the polynomial discovery function with reclamation policies. Figure 9 shows the paths of NPV with different terminal periods, and this simulation result is created by running simulation 300 times with different terminal periods. We assume that NPV reaches maximum value with the terminal period of 300 because the annual growth rate of NPV is zero. Under this assumption, NPV with the terminal period of 32 reaches 92.2% of the maximum, that with the terminal period of 73 has 99.9%, and that with terminal period of 125 obtains 100% of the maximum. After the terminal period of 125, NPV remains at the same value.

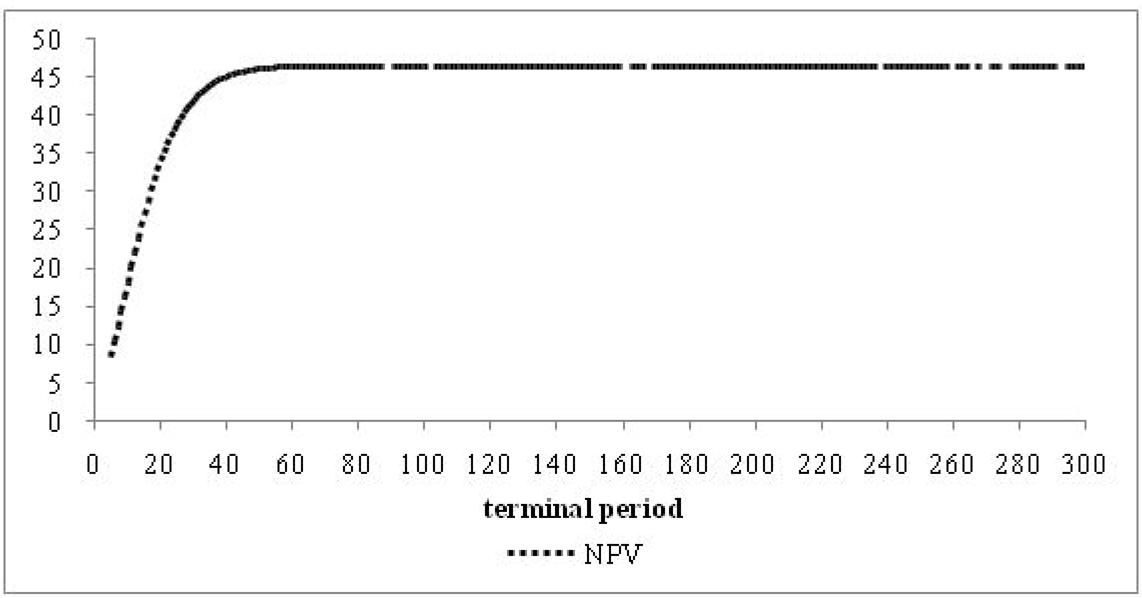

Figure 9: Paths of NPV with different terminal period ($\$ \times 10^6$)

Next, we consider the annual growth rate of NPV. The annual growth rate of NPV can be a touchstone for a firm to make decision because the firm figures out the rate of increase in NPV by extending the shutdown period another year. The annual growth rate reaches right above 10% when the terminal period is 11. The annual growth rate becomes 5% with the terminal period of 17, and it decreases to 3% with the terminal period of 21. The annual growth rate of NPV is 4.76×10^{-8} % with the terminal period of 300.

6 Discussion on Bonding Structure

Cash Bond v.s. Financial Bond

We focus on a comparison of alternative forms of a cash bond in this discussion. The current and primary form of cash bonding is in a lump sum form where payment goes to the agency and the funds are placed in the government current accounts versus a financial bond that is set up like an escrow account where the fund can grow at a low risk interest rate and is set at an initial level to grow to the level needed to cover reclamation expenditures. The posted bond is returned to the operating firm after final reclamation is successfully completed. This process which includes both production and reclamation activities takes approximately 25-30 years. Although BLM returns the same amount of posted bond to the firm, the posted bond could have been invested on low-risk assets, such as Treasury bond of the United States in the perspective of efficient utilization of financial resource (Davis, 2014). We denote a bonding structure which is allowed to invest on other financial assets as a financial bond. The major benefit of financial bond is that the nominal value of bond increases while the firm operates production.

The representative firm posts the reclamation bond, B_0, in the initial period. We assume that posted reclamation bond is not of adequate size to complete reclamation until the end of the lease period when they cap the well. So there are two scenarios that we evaluate: The Firm abandons the well before before the terminal period or finishing the reclamation after the terminal period. Because the financial bond invested on low-risk assets grows the nominal value of posted bond, the financial bond has advantages over the simple cash bond.

Reclamation Policy in relation to the Bonding Structure

The uncertainty with regards to the surrounding reclamation bond will not be eliminated, and it is difficult to predict the timing of modification to current regulations when firms start production. We think that interim reclamation mitigates the risk of paying unexpectedly large reclamation cost after production completes. The effect of time discounting decreases the final reclamation cost in real dollars, and the effect of time-discounting is one of the motivations for firms to postpone as the simulation results with different terminal periods show in Figure 9; however, external risks increase the expected final reclamation cost realistically, such as modification and enactment of regulations, land degradation over periods and spills from the wells.

When we consider the optimal timing for firms to perform interim reclamation, earlier is better for both firms and society to perform interim reclamation because of the sharp decline of production rates of wells over time. Nelson et. al (2009) reported the decline in the production rate by collecting the data on daily production rates of natural in Wyoming. The average production rate decreases from 537 Mcf per day to 191 Mcf per day for five years. The average production rate decreased 64.4% in the Wind River Basin in Wyoming. Nelson selected the initial year for this production-rate comparison at approximately two years after wells commenced production "to eliminate early transients and early changes in equipment." Thus, we think it efficient for firms to commence interim reclamation earlier because they can afford due to the sufficient production. Large firms which have myriad of well-sites can constantly gain sufficient profits from the wells to continue their business, but small-sized firms may increase the risk of "walk-away" by postponing the interim reclamation because of the sharp decline in the production rate.

we describe how interim reclamation improve the current bonding structure to integrate the discussions in this chapter. The final reclamation cost is denoted as C_{FR}, and the sum of interim reclamation cost is denoted as $\sum C_{IR}$ in Figure 10. The unit of vertical axis is nominal dollar. The final reclamation costs $(B_0 + B_1)$ at the terminal period, T, if the firm does not perform interim reclamation. As is the case with the current bond requirement, the firm pays the fixed blanket bond for B_0. In reality, the size of B_1 is unknown because B_1 can be calculated by the gap between the final reclamation cost and initial bond; however, we assume that the firm knows the size of disturbed area at the terminal period. If firms always comply with final reclamation, the opportunity cost of posting the initial cash bond can be eliminated because the governmental agency does not have to give incentives to the firms. When the firm continues production until T, the shaded area $C_{FR}(S_T)$ is the final reclamation cost.

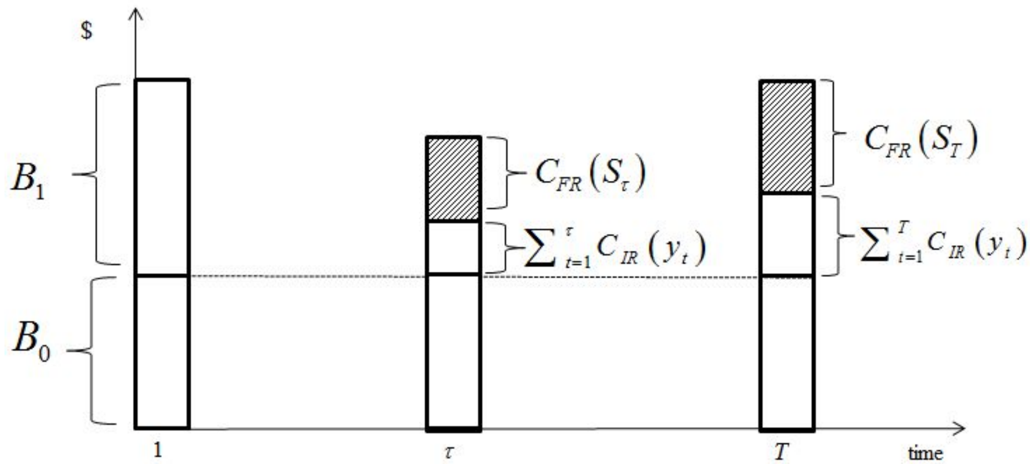

Figure 10: The effect of interim reclamation to the final reclamation cost

We consider a case that firms may "walk-way" in Year τ. When firms perform interim reclamation, the part of total reclamation costs is paid by interim reclamation. We think that the risk of "walk-away" at τ depends on the size of firms because of the sharp decline in production rate over time. The governmental agency incurs the shaded area that is equal to the final reclamation cost, $C_{FR}(S_\tau)$, if the firm shirks in Year τ. As we showed the optimal path of interim reclamation in Figure 5, the appropriate combination of interim reclamation and MADA makes firms reclaim the land disturbances at the early point of the production process.

Finally, we consider that the optimal reclamation bond needs to be estimated by including the potential risks of shirking. Because the interim reclamation reduces the final reclamation cost that must be covered, the optimal size of reclamation bond can be lowered; thus, the reclamation bond creates less liquidity constraint when firms perform interim reclamation.

7 Conclusion

We model the discrete time dynamic optimization model based upon Pindyck but with reclamation requirements and bonding attached to the model (16). The results follow implications of the theory of exhaustible resources. The modeling framework will allow a number of extensions to be attached, including ecosystem objectives, asymmetric information, and stochastic programming. The modeling then provides a more comprehensive picture of oil and gas development that includes efforts to return land to close to its original state. The Bureau of Land Management's policy of maximum allowable disturbed area is a positive regulatory innovation for the Rocky Mountain West with large areas of public lands. It is likely that MADA is as good as or better than the bond for insuring due diligence in reclamation obligations.

Second, the simulation results show the optimal paths of variables for two models. As theory would suggest adding costs reduces the percentage of recoverable reserves that are extracted. Simulations with different forms of estimated and calibrated cumulative discovery functions to show how the discovery functions influence the optimal paths of variables.

Finally, we explore the economic interrelationship between reclamation and restoration policy, environmental bonding rules, and liability Figure 10. The dilemma that policy makers face is that while low bond rates increase likelihood of firms "walking away" from their obligations generating higher environmental and fiscal opportunity costs, high bond rates mean higher market based opportunity costs where firms could be generating public and private surplus elsewhere if capital was not tied up in bond value. While it might seem like it is a straightforward comparison, complications arise as to the distribution of benefits across income classes and geographic areas where some areas bear the costs other areas bear the benefits.

Uncertainty about what we are actually losing is another potential problem. We consider that a system with just final reclamation increases the risk of firms "walking away" without completing final reclamation; however, a system with interim reclamation attaching a "claim" to early profits increases the likelihood that more reclamation will be done.

In future work, we plan to create a stochastic model to represent the effect of the risk of "walk-away" without completing final reclamation, but also include ecosystem service values with a regulatory agency objective function.

References

[1] Andersen, M., Coupal, R., and White B.Spring 2009. *"Reclamation Costs and Regulation of Wyoming's Oil and Gas Industry"*. VIII(1) Western Economic Forum.

[2] Buto S., Kenney T., Gerner S. (2010) Land disturbance associated with oil and gas development and effects of development-related land disturbance on dissolved-solids loads in streams in the Upper Colorado River Basin, 1991, 2007, and 2025. U.S. Geological Survey Scientific Investigations Report 2010-5064.

[3] Constanza, R. and C. Perrings. 1990. "A flexible assurance bonding system for environmental management." *Ecological Economics* 2, 57-75.

[4] Cooter, R., Ulen, T., 2000. *Law and Economics.* Addison-Wesley, Reading (MA).

[5] Davis, L. 2014. "Bonding Requirements for Natural Gas Producers." EI Haas Working Paper: WP-232.

[6] Deacon R. 1993. "A Taxation, Depletion, and Welfare: A Simulation Study of the U.S. Petroleum Resource." *Journal of Environmental Economics and Management* 24(2): 159-187.

[7] Energy Information Administration. 2014. Accessed 1 May 2014. http://www.eia.doe.gov/.

[8] General Algebraic Modeling System (GAMS): Version 24.0. 2013 Washington, DC.

[9] Gerard, D. 2000. The Law and Economics of Reclamation Bonds. *Resources Policy* 26(4): 189-197.

[10] Nelson, P., Trainor, P., Finn,. T. 2009. Gas, Oil, and Water Production in the Wind River Basin, Wyoming. Geological Survey Scientific Investigations Report 2008-5225: 24.

[11] Perrings. C. (1989) Environmental bonds and environmental research in innovative activities. Ecological Economics. 1(1): 95-110.

[12] Pindyck. R. (1978) The Optimal Exploration and Production of Nonrenewable Resources. Journal of Political Economy. 86(5): 841-861.

[13] Shogren J., Herriges J., and Govindasamy R. 1993. "Limits to Environmental Bonds." *Ecological Economics* 8(2): 109-133.

[14] Sult D. 2004. "The Effect of Coal Mine Bonding Systems on the Probability of Reclamation." Unpublished PhD Dissertation, Colorado School of Mines.

[15] Webber B., and Webber D. 1985. "Promoting Economic Incentives for Environmental. Protection in the Surface Mining Control and Reclamation Act of 1977: An Analysis of the Design Implementation of Reclamation Performance Bonds." *Natural Resource Journal* 25(2): 389-414.

[16] Wächter, A., and Biegler, L. 2006. "On the Implementation of a Primal-Dual Interior Point Filter Line Search Algorithm for Large-Scale Nonlinear Programming", *Mathematical Programming* 106(1): 25-57.

[17] Western Organization of Resource Councils. 2004. "The Need for Stronger Federal Oil and Gas Bonding Requirements." Working paper.

[18] U.S. Bureau of Land Management. 2006. "Final Environmental Impact Statement for the Proposed Jonah Infill Drilling Project, Sublette County, Wyoming." Bureau of Land Management, Pinedale Field Office, Pinedale, Wyoming, and Rock Springs Field Office, Rock Spring, Wyoming. BLM/WY/PL-06/006+1310.

[19] BLM. 2011. Continental Divide-Creston natural-gas development project: preliminary draft environmental impact statement. Rawlins, WY, USA: Department of the InteriorBureau of Land Management Rawlins Field Office. 561 p. Technical Appendix E.

[20] Wyoming Oil and Gas Commission Committee (WOGCC). Accessed 1 May 2014. http://wogcc.state.wy.us/.