Modeling Petroleum Productivity in the U.S. Gulf of Mexico Outer Continental Shelf (OCS) Region

Omowumi O. Iledare, Allan G. Pulsipher and Williams O. Olatubi

Productivity generally refers to the amount of output that can be produced with a given input. However, because measures of inputs and outputs can vary considerably, several indicators of productivity in petroleum resource development are possible. The more meaningful indicators of productivity that relate directly to upstream activities include drilling success rates, average discovery size, finding rates, and yield per effort. In this paper, we examine the performance of the oil and gas upstream industry in the Gulf of Mexico OCS region using these indicators. Further, using econometric modeling techniques, we determine empirically the effects of depletion, technical progress, economic and policy incentives, structural changes and market conditions on the returns to exploration activities in the U.S. Gulf of Mexico OCS. The model results confirm expectations of diminishing returns to wildcat drilling on the OCS due to resource depletion, while the combined effects of economic incentives, institutional restructuring, and technical progress have mitigated significantly the declining trend in wildcat drilling productivity in the region.

1. Introduction

Productivity generally refers to the amount of output that can be produced with a given input. However, because measures of input and output can vary considerably, several indicators of petroleum drilling productivity are possible. The more meaningful indicators of productivity that relate directly to upstream activities include drilling success rates, average discovery size, discovery rate, and yield per effort (Bohi,1997).

Success rate measures the proportion of drilling that successfully finds and adds new reserves to inventory of reserves with distinction as to the type of drilling activity. There are two major categories of drilling activity--exploratory drilling and development drilling. Exploratory drilling, which can be classified into two subgroups, is a more risky activity than development drilling. The more risky of the two exploratory subgroups is called wildcat drilling. This form of exploratory drilling occurs when a well is drilled in search for a new field on a structure or an environment that has never been productive or when a well is drilled outside the limits of a proved area of a petroleum reservoir. The other exploratory drilling sub-category is that of drilling a well in search of a new petroleum reservoir below or above the deepest proved reservoir, or drilling an outpost or extension test well in a partly developed reservoir.

The authors are (respectively) Associate Professor-Research, Marathon Oil Company Professor of Energy Policy, and Post-Doctoral Research Associate at the Center for Energy Studies, Louisiana State University.

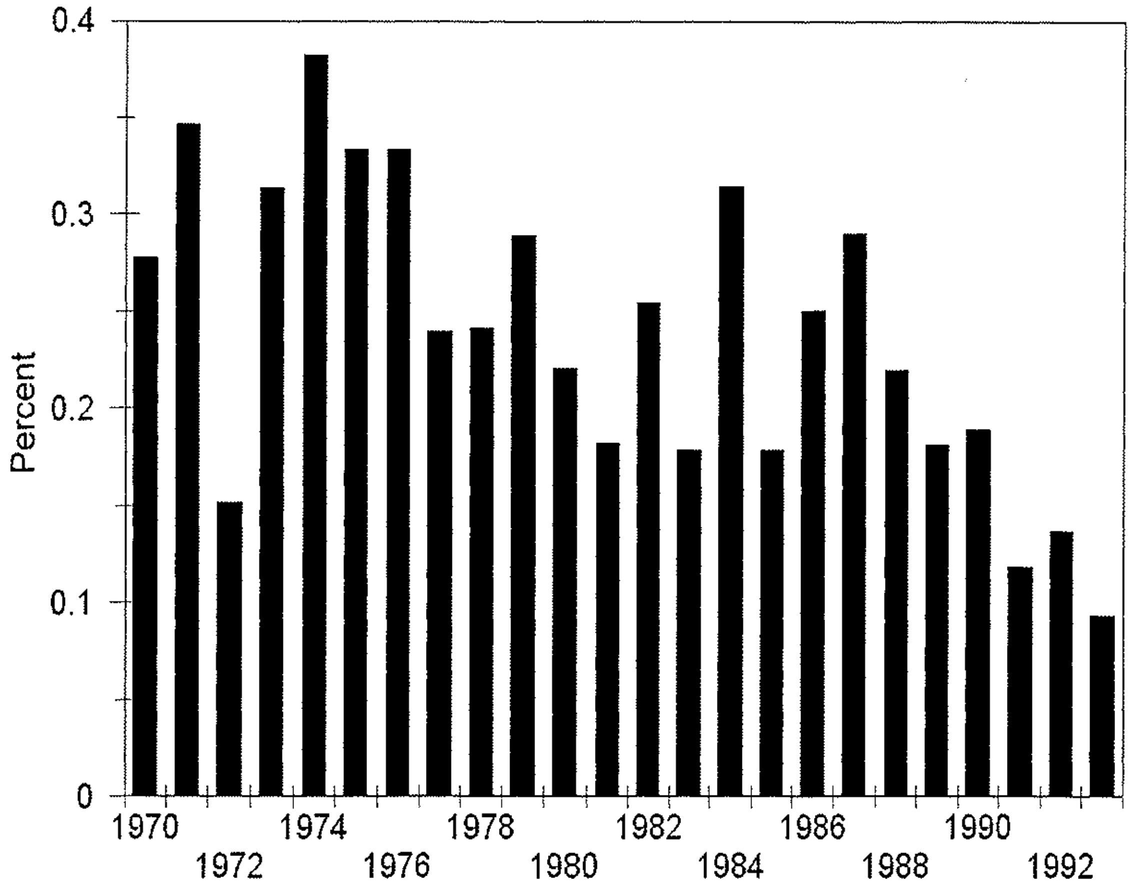

Figure 1: Trend in Wildcat Drilling Success Rate

Development wells are wells drilled to produce or increase production of discovered hydrocarbons during an exploration process.

Figure 1 shows the trend in the success rate of wildcat wells in the Gulf of Mexico OCS region for the period 1970 through 1993. The proportion of successful wildcat wells declined from a high of nearly 40 percent in 1973 to a low of less than10 percent in 1993. On average, one out of five wildcat wells discovered a new field in the Gulf of Mexico OCS region over the past twenty years.

The average size of petroleum discovery is another measure of petroleum drilling productivity. The measure of output in this productivity definition is the amount of petroleum reserves discovered and the measure of input is the number of successful wildcat wells or total successful footage drilled over a stipulated period, say, one year. Figure 2 presents the trend in average size of discovery on the OCS since 1970.

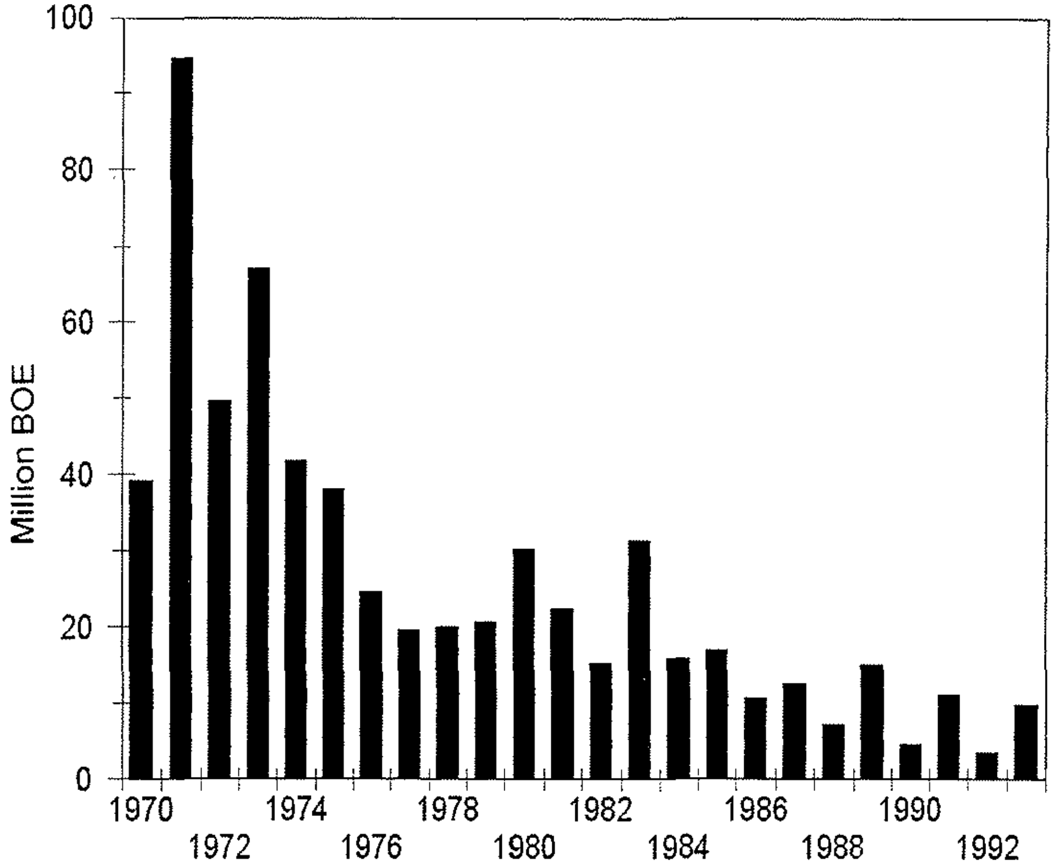

Figure 2: Trend in Average Size of Petroleum Discovery on the OCS

The trend in average size of discovery is declining in an overall sense with an increasing number of wildcat wells, even as net operating profit declines from a high of about 14 dollars in 1982 (see Figure 3). The interval estimate of the average discovery size over the past twenty years at the 95 percent confidence level is 20 -30 million BOE. The range of average size of discovery was 90 million BOE in 1971 and about 5 million BOE in 1992.

Another measure of petroleum drilling productivity is the discovery rate. This is defined as the ratio of total discovery to total wildcat drilling effort. It is identically equivalent in definition to wildcat finding rate, the product of average discovery size and the success rate. Figure 4 presents the trend in discovery rate (wildcat finding rate) since 1970.

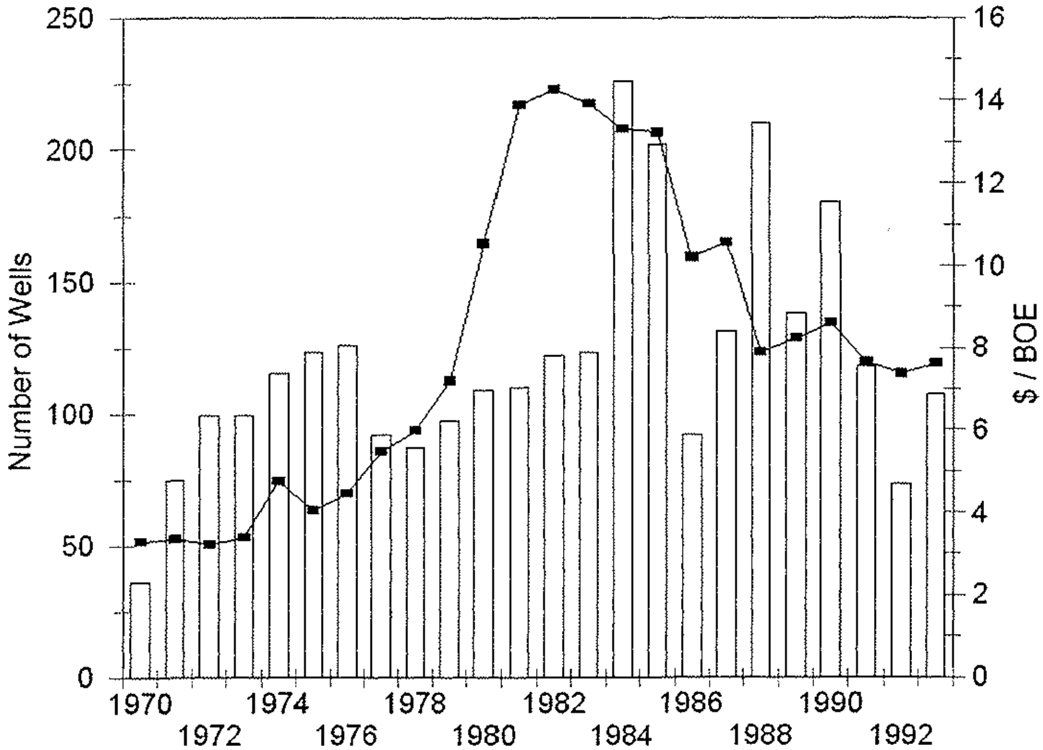

Figure 3: Trends in Wildcat Effort and Net Operating Profit

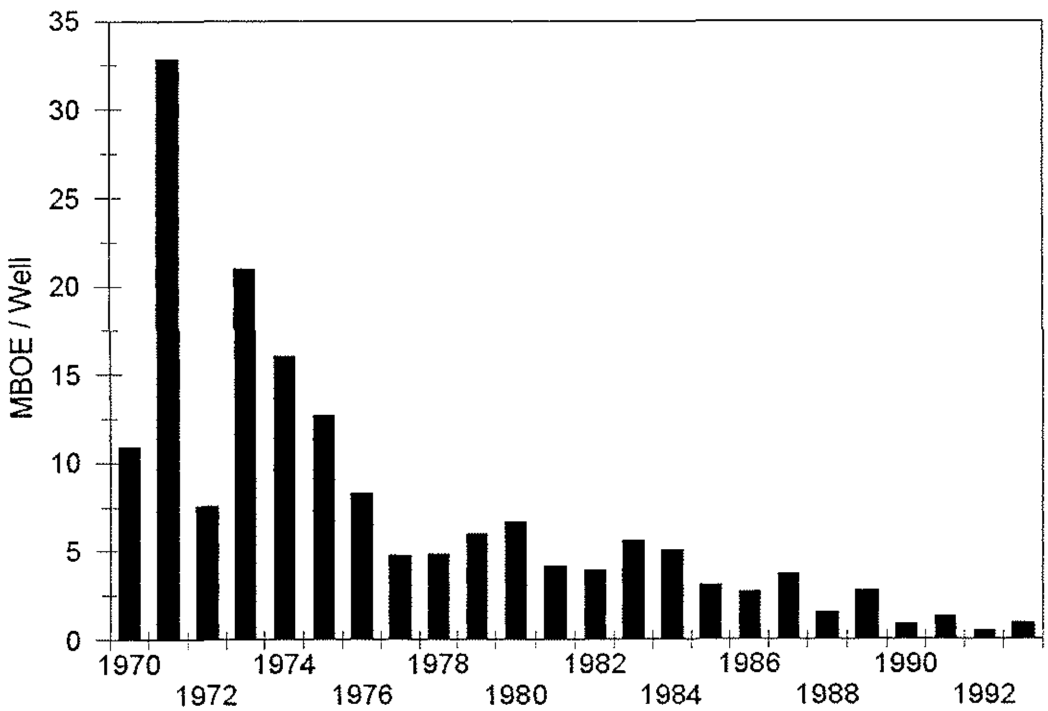

Figure 4: Trend in Wildcat Finding Rate

As evident from Figures 1, 2, and 4, every measure of wildcat productivity has been declining since 1973 in an overall sense. There are, however, some occasional spikes along the declining path. The occasional spikes are more evident in Figure 2, which describes the trend in the success rate of wildcat drilling in the U.S. Gulf of Mexico OCS. It is suggested that the shifting of the productivity trend with respect to successful wildcat drilling above the declining path is probably as a result of institutional changes in the industry in addition to the effects of technical progress on drilling choices and operations (Bohi, 1997). The industry has become more selective regarding the prospects they choose to drill through successful applications of 3-D seismic information technology. The 3-D seismic technology makes it possible to locate smaller oil and gas deposits than 2-D seismic survey could. Thus, a relatively reasonable hypothesis to be examined is whether technical progress has been effective enough to mitigate the adverse effect of resource depletion on petroleum drilling productivity on the Gulf of Mexico OCS.

2. Petroleum Productivity Specification

Previous attempts to model petroleum drilling productivity, especially the finding rate of reserves or yield per effort, in a mature petroleum basin such as the U.S. Gulf of Mexico OCS, the U.S. Lower 48 States, and the coastal onshore basins in Louisiana and Texas, have assumed that new reserves are the output of the drilling process subject to resource availability, economic and policy incentives, and technology, as well as the stochastic nature of petroleum drilling outcomes[1]. The model presented in this paper assumes these fundamental concepts in addition to the generalized petroleum discovery process assumption that larger petroleum reservoirs are likely to be discovered first. Thus, if reservoirs discovered first contain most of the reserves in place, then the cumulative reserves added will tend to decline as cumulative drilling effort increases (Uhler, 1979).

The functional relationship between cumulative discovery and cumulative effort can be specified using a non-linear petroleum reserve production function of the form (Porter, 1992)[2]:

$$Y(t) = \alpha_0 e^{\alpha_1 Z(t)} W(t)^{\alpha_2} \quad (1)$$

where

Y (t) = cumulative total discoveries since t-n:n<t;

W(t) = cumulative wildcat wells since t-n:n<t;

Z(t) = other intervening factors such as technical progress, economic/market conditions, learning effects, etc., and α_0, α_1, and α_2 are parameters to be estimated.

Differentiating equation (1) with respect to W(t) yields a behavioral equation which describes the wildcat finding rate of new hydrocarbons--reserve additions per additional wildcat wells as follows:

$$y(t) = \alpha_4 e^{\alpha_2 Z(t)} W(t)^{\alpha_3} \quad (2)$$

where

α_4 = - ($\alpha_0 * \alpha_3$), the ultimate discovery rate

α_2 = a measure of an increase in drilling productivity with respect to changes in other intervening factors such as technical progress--improvements in seismic technology, and/or the effectiveness of drilling technology e.g. horizontal drilling, which may result in higher successful drilling rates or an increase in the level of recoverable reserves;

α_3 = the effects of cumulative drilling, a proxy variable for resource depletion and accumulated geological knowledge, on drilling productivity.

[1]S(ee Kang and Berg (1994), Porter (1992), Walls (1994), Deacon et al (1990), Griffin and Moroney (1985), Iledare and Pulsipher (1999).

[2]It should be noted, however, that the above functional form is only one of many possible decreasing functions that may be used to relate cumulative new reserves to cumulative effort (Iledare (1995); Porter (1992) and Forbes and Zampelli (1996)).

3. Empirical Results and Analysis Data

The database used to estimate (2) contains time series observations over the period 1970 - 1993 for Texas and Louisiana OCS regions. The main source of data is the U.S. Department of the Interior(DOI)/Minerals Management Service (MMS) database on *Estimated Proved and Unproved Oil and Gas Reserves for the Gulf of Mexico* downloaded from the internet *(URL: www.gomr.mms.govpub...eeasci/geologic/estimated1996.html)*. A brief overview of some of the model variables and procedures for generating our data series is given below.

Cumulative Reserves Discovered, Y(t). The series is extracted from the database on 920 proved fields in the Gulf of Mexico (U.S. DOI/MMS, 1996). To arrive at combined hydrocarbon reserve estimates in million BOE (MMBOE), natural gas reserves in BCF is multiplied by 0.18 and added to the oil reserve figure in million barrels..

Cumulative Wildcat Drilling Effort, W(t). Drilling effort is measured in number of wildcat wells drilled. The series is calculated as the sum of total wildcat wells drilled since 1970. The data series is extracted from the MMS data file downloaded from the internet *(URL:www.gomr.mms.govpub...freeasci/well/boreholedatadfn.html)*. *W(t)* is a proxy variable for resource depletion and cumulative geological knowledge.

Z(i, t) represents vectors of other intervening factors such as technical progress, economic and market conditions that may be responsible for shifting the time path of the wildcat finding rate.

In order to estimate Equation 2, a linear approximation is assumed. The estimated equation is thus specified as follows to obtain the relevant parameters estimates:

where

$$\log y(t) = \alpha_4 + \alpha_3 \log W(t) + \alpha_5 \pi(t-1) + \alpha_6 S(t) + \alpha_7 D86 + \epsilon(t) \quad (4)$$

$y(t)$ = wildcat finding rate, MMBOE per wildcat well drilled
$W(t)$ = cumulative wildcat wells drilled since 1970
$\pi(t-1)$ = expected net unit operating profit measured as immediate past year profit
$S(t)$ = probability of new discovery, a proxy for technical progress
$D86$ = dummy variable equals to 1 from 1986 onward
$\epsilon(t)$ = the random error term

The expected net operating profit represented by π is a proxy for economic condition. This is defined as the net inter-temporal value of petroleum production over the life of an incremental barrel of new reserve. π is calculated as the discounted future after-tax value of a barrel of prospective new recoverable reserves such that:

$$\pi = (1-\zeta)(1-\omega-\rho)\frac{\lambda}{\lambda+\phi}P^{e} \quad (3)$$

where a barrel of new reserve additions is assumed to be extracted at an exponentially declining rate (λ) over the reserve-life. P^e is the expected price of hydrocarbon in the Gulf of Mexico OCS region; ζ is the corporate income tax rate; ω is the proportion of price consumed by extraction costs; ρ equals royalty rate; and ϕ is the discount rate. The expected price series is approximated as the weighted average of the real price of oil and gas in the Gulf of Mexico OCS converted to $/BOE on the basis of recoverable oil and gas reserves. The series is deflated using the Producer Price Index, PPI, (1982=100).

The effect of technical progress is captured by the inclusion of success ratio represented by S in the specification. As technology improves one would expect that the success ratio will also increase, *ceteris paribus*. However, the effects of technical progress on discovery rate with time may not necessarily increase at an increasing rate indefinitely. One obvious reason for this is the fundamental assumption in the discovery process that larger deposits are necessarily discovered first. With advances in technology, however, only a few wildcat wells may become necessary to discover a given amount of new reserves, *ceteris paribus*, with time.

Finally, a dummy variable is included to capture the crude oil market conditions. The dummy variable is equal to 1 in the years 1986 onward reflecting the collapse of the world oil market in 1986 and institutional changes that followed, including the rising trend in deep water wildcat activity. Table 1 presents the descriptive statistics of selected variables used to estimate equation (4).

Estimated Results

Equation (4) was estimated using the Ordinary Least Square (OLS) procedures on productivity data for the Gulf of Mexico OCS from 1970-1993. A first order serial correlation assumption was imposed to normalized the error structure such that:

$$\epsilon(t) = \rho\epsilon(t-1) + \varpi(t) \quad (5)$$

where ω is distributed normally with a zero mean and constant variance.

Table 1. Descriptive Statistics of Model Variables, 1970-1993

Model Variables	**Mean**	**Maximum**	**Minimum**	**Standard Deviation**
Net operating profit, π ($/BOE)	8.02	14.26	3.23	3.73
Average size of discovery, (MMBOE/successful wildcat well)	25.92	94.70	3.54	21.18
Wildcat wells drilled, dW (#)	120	226	36	45
Success wildcat wells completed, $S*dW$ (#)	29	7 1	10	14
Reserve additions per well, y (MMBOE / well)	6.96	32.83	0.48	7.43
Wildcat successful ratio, S (%)	23.80	38.26	9.34	7.77

Table 2 presents the estimated parameters of equation (4) after correcting for serial correlation. The estimated parameter describing the effect of cumulative drilling effort on wildcat finding rate is negative and significantly less than unity. This is an indication of diminishing returns to wildcat drilling in the U.S. Gulf of Mexico OCS region. The positive sign of the coefficients of technical progress, measured as changes in success rate, however, suggests that technical progress to some extent has a mitigating effect on the adverse impact of depletion.

Table 2: OLS Regression Estimates
(t-statistics in parenthesis)

Variable	Wildcat Finding Rate
Intercepts	5.2582* (7.3010)
log (*W*)	-0.7741* (-6.8209)
π	0.0412** (2.3010)
S	0.0568* (6.8242)
D86	-0.2914*** (-1.8637)
$\varepsilon(t-1)$	-0.6749* (-3.5444)
Panel Observations	22
Adjusted R^2	0.905
Error of Regression	0.293

* significant at 1%
** significant at 5%
*** significant at 10 percent

The positive coefficient of the expected net economic benefit on the wildcat finding rate in addition to its mitigation effects on the impacts of resource depletion of finding rate, reflects the economic aspects of reserve additions. The amount of recoverable reserves may increase with favorable economic conditions as the life of producing properties naturally extends and the costs of production continue to be recoverable (Hannesson, 1997). Contrary to expectation, however, the coefficient of the dummy variable is negative, but only marginally significantly different from zero at 10 percent level, suggesting that the collapse of crude oil prices in the late 1980s shifted marginally downward the decline path of the wildcat drilling productivity. This, however, does not mean that the expected returns from increasing drilling activity in the deep waters of the OCS, and changes in the institutional framework of the industry during these periods have yielded no significant positive impact on the wildcat finding rate. As data on new discoveries from deep water activities becomes readily available, the empirical results will be revisited.

Interpretation of Results

The magnitude of the coefficient of cumulative wildcat drilling effort provides a direct measure of the responsiveness of productivity to resource depletion. As expected, the sign of the coefficients is negative and statistically significant. On average, the estimated impact of resource depletion on productivity on the OCS estimated to be less than unity (-0.774), suggesting there is evidence of diminishing returns and an inelastic response of productivity to cumulative wildcat drilling.

The regression results also show a statistically significant impact of economic conditions and success rate on wildcat finding rate in the U.S. Gulf of Mexico OCS region. The estimated annual impact of a unit change in technical progress (success rate), on average, is 5.68 percent in comparison to an annual impact of 4.12 percent positive change for every one unit change in net operating profit

Measured in terms of elasticity,[3] the responsiveness of the finding rate of petroleum with respect to net operating profit of firms operating on the Gulf of Mexico OCS is 0.33, and the average responsiveness with respect to a percent change in wildcat success ratio, our proxy for technical progress, is also estimated as 0.013 for the period 1970-1993. In other words, the responsiveness of wildcat finding rate of petroleum in the Gulf of Mexico OCS is inelastic with respect to changes in net operating profit and technical progress. Thus, in an overall sense, the negative impacts of resource depletion and institutional changes according to our regression results were significantly reduced by the effects of net operating profit and technical progress. However, in an aggregate sense, the overall positive impacts of technical progress and economic incentives during the 1970-1993 period did not fully mitigate the overall effects of resource depletion on wildcat finding rate of petroleum in the Gulf of Mexico OCS region.

4. Summary and Conclusions

In this paper a single equation model of petroleum discovery per wildcat well for the U.S. Gulf of Mexico OCS is specified as a function of cumulative effort, success ratio, net operating profit, and a dummy variable to capture the effects of the collapse of the global crude oil prices and institutional changes in the oil and gas industry. The model equation was estimated using OLS regression with correction for serial correlation on time series data for the period 1970-1994 and dummy variable equals to 1 for the period 1987 onward.

The estimated model was applied to analyze the impact of depletion, economic condition, technical progress, and institutional changes on the finding rate of petroleum wildcat drilling on the U.S. Gulf of Mexico OCS. Our empirical results indicate strong statistical evidence to suggest that the positive impact of technical progress and of economic incentives on wildcat finding rate of petroleum did not fully mitigate the depletion effects but significantly reduced the effects during our sample period. We estimated the impact of the collapse of world crude oil prices in 1986 on the wildcat petroleum finding rate to be only marginally significant in the U.S. Gulf of Mexico OCS.

The results presented above are conjectural as perspectives on the competing influences of technical progress, economic incentives and petroleum resource depletion on petroleum reserve additions per drilling effort in mature petroleum basins vary significantly among oil and gas supply analysts: Cleveland (1997), Fisher (1994), Iledare and Pulsipher (1999), and Forbes and Zampelli

[3] In general, if a functional formulation of the relationship between a dependent variable Y and an exogenous variable X is such that log Y = a + bX, then the responsiveness of Y with respect to X is b*x, where x is the expected value of X.

(1996). This analysis is unique, however, in that it deals with a specific region, the U.S. outer Continental Shelf rather than the entire U.S. in the aggregate. The paper is also unique in the sense that finding rate of petroleum reserves is defined with respect to a specific form of drilling activity, wildcat drilling, rather than using total drilling–wildcat, other exploration, and development-- activity.

References

Bohi, Douglas R. 1997. *Changing Productivity of Petroleum Exploration and Development in the U.S.* Resources for the Future Discussion Paper, January 1997, Washington, D. C.

Cleveland, Cutler J. and Robert K. Kaufmann. 1997. "Natural Gas in the U.S.: How Far Can Technology Stretch the Resource Base?" *The Energy Journal* 18 (2): 89-108.

Deacon, R. T. et al. 1990. *Taxing Energy: Oil Severance Taxation and the Economy.* New York, NY: Holmes and Meier.

Fisher, W. L. 1994. "How Technology Has Confounded U.S. Gas Resource Estimators." *Oil and Gas Journal* 92:100-107.

Forbes, K. F. and E. M. Zampelli. 1996. "The Returns to Oil and Gas Exploration: Has Technology Dominated the Effects of Depletion?" Paper presented at the 17th Annual North American Conference of the United States Association for Energy Economics, October 29, 1996, Boston, MA.

Griffin, J. M. and J. R. Moroney. 1985. *The Economic Impact of Severance Taxes: Results From an Econometric Model of The Texas Oil And Gas Industry.* Report to the Texas Mid-Continent Oil and Gas Association.

Iledare, Omowumi O., Allan G. Pulsipher and Robert H. Baumann. 1995. "Effects of an Increasing Role for Independents on Petroleum Resource Development in the Gulfof Mexico OCS Region." *The Energy Journal* 16 (2): 59-76.

Iledare, Omowumi O., and Allan G. Pulsipher. 1999. "Sources of change in productivity of petroleum exploration and development in onshore Louisiana in the U.S., 1977-1994." *Energy Economics* 21 (3): 261-271.

Kang, S. W. and M. D. Berg. 1994. "World Crude Oil Exploration and Extraction." In *Advances in the Economics of Energy and Resources* (J. R. Moroney, ed.), Greenwich, CT: Jai Press, Inc.,Vol 8, 135-157,

Porter, E. D. 1992. *U.S. Petroleum Supply: History, Prospects, and Policy Implications.* American Petroleum Institute (API) Research Study #064, Washington, D.C.: American Petroleum Institute.

U.S. Department of Energy, Energy Information Administration. 1995. *U. S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves.* DOE/EIA-0216(1993), Washington, D C.

Uhler, R. S. 1979. "The Rate of Petroleum Exploration and Extraction." In *Advances in the Economics of Energy and Resources* (R. Pindyck, ed.), Greenwich, CT: Jai Press, Inc.,Vol 2, pp 93-118.

Walls, M. A. 1994. "Using 'Hybrid' Approach to Model Oil and Gas Supply: Case Study of the Gulf of Mexico Outer Continental Shelf." *Land Economics*, 70 (1): 1-19.

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