The Option Value of Scientific Uncertainty on Pest - Resistance Development of Transgenic Crops

by

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Abstract. In this paper the option value of waiting under scientific uncertainty will be derived using the difference between the geometric Brownian motion and the mean reverting process by applying contingent claim analysis. The results will be compared with those generated by either using a geometric Brownian motion or a mean-reverting process only. An example based on the decision problem whether or not to release herbicide tolerant rape seed in the EU will be used to illustrate the differences. The paper contributes to the suggestion made by biologists to further analyze the sensitivity of the results using the real option approach, provides insights about the magnitude of error that can be made by choosing the wrong process, provides a solution to the problem and highlights the implication for the decision of whether or not to release transgenic crops. The results show that scientific uncertainty is less important than one would expect at first hand.

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JEL: Q, D81, D61.

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1. Introduction

Economists have proposed the real option theory for the ex-ante valuation of costs and benefits from transgenic crops. Farrow, Morel, Wu and Casman (2001) in their paper model the uncertain incremental net-benefits from transgenic crops by using a geometric Brownian motion process[1]. The build up of pest resistance is included by adding a jump process describing the decay of resistance. Irreversibilities, *I*, are explained by possible gene drifts from transgenic crops. Wesseler and Weichert (1999) and Wesseler (2002) used almost the same approach. Wesseler (ibid.) included in the later paper the possibility of irreversible benefits, *R*. Irreversible benefits were defined as the reduction of irreversible costs of the alternative technology. Gilligan (2002) in a review of Farrow et al. (ibid.) and Wesseler (ibid.) argued that further discussion on the sensitivity of the results is needed in a dialogue with biologists. One assumption made in both papers is that resistance is inevitable. This does not necessarily have to be the case. As Gilligan (ibid.) clearly pointed out gene drift may lead to invasion but invasion may not lead to persistence and pest resistance may occur but may also break down again over time. That is to say that there is not only uncertainty about the economic variables but also uncertainty about the biological processes. This adds uncertainty to the models used by Farrow et al. and Wesseler and will have two effects. On the one hand, this will lead to uncertain irreversible costs; on the other hand it will affect the incremental net-benefits from transgenic crops.

[1] The incremental net-benefits are the differences between transgenic and non-transgenic crops.

Let's ignore for a while the uncertainties about the irreversible costs by assuming they are constant[2], and concentrate on the incremental net-benefits.

If the incremental net-benefits of a transgenic crop will be negatively affected over time due to invasion, they will decrease, if not, it can be assumed they will continue to grow. Both situations are not unfamiliar to economists. A geometric Brownian motion can model the uncertain growth as has been done by Farrow et al. (ibid.) and Wesseler (ibid.). If pest resistance occurs, the decrease over time can be modeled by using a mean reverting process. The problem then would be to decide which kind of process to use.

A solution to the problem would be simple if by using an appropriate econometric method time series data could be tested to decide which process to use. As Dixit and Pindyck (1994) and others (e.g. Gjolberg and Guttormsen, 2002) have pointed out the results are ambiguous. Depending on the time frame used, the tests either lead to a rejection or acceptance of a non-stationary process. They recommend choosing the process not based on time series analysis but based on theoretical grounds. This is a straightforward recommendation, if scientists can agree about the relevant theory. But as the case for transgenic crops shows (Gilligan ibid.), there is no scientific certainty about the stochastic benefits from transgenic crops. Scientists are aware of the problem, but have no method available that tells them which model to choose. This is what in this context will be called scientific uncertainty.

From a decision makers point of view this may not be important if different processes do not lead to different recommendations. As Wesseler (2001) has pointed out, the choice of a stochastic process may but not necessarily will lead to different recommendations. Figure 1 shows a comparison between a geometric Brownian

[2] That this is a useful assumption has been explained by Wesseler (ibid.).

motion and a mean reverting process and the decision to release transgenic crops, where it is assumed that each process represents a scientific belief or view about the benefits from transgenic crops. The situations depicted under quadrant I and quadrant IV lead to unequivocal decisions: either immediate release, quadrant I, or delaying the release, quadrant IV. On the other, hand the situations depicted in quadrant II and III are equivocal: depending on the stochastic processes either immediate release or delaying the release is economical. Specifically the situation in quadrant III is of importance as the geometric Brownian process dominates the mean reverting process by almost first degree of stochastic dominance (FSD).[3]

	I	II
GB[1] MR[2]	Release Release $V \geq V^*_{GB} \wedge V \geq V^*_{MR}$	Delay Release $V \leq V^*_{GB} \wedge V \geq V^*_{MR}$
	III	**IV**
GB MR	Release Delay $V \geq V^*_{GB} \wedge V \leq V^*_{MR}$	Delay Delay $V \leq V^*_{GB} \wedge V \leq V^*_{MR}$

[1]GB: geometric Brownian motion; [2]MR: mean reverting process.

Figure 1: Possible Combinations of Results Under Different Belief Systems (Wesseler, 2001).

These observations lead to an important question: *Do we have to choose between different processes or is it possible to combine the processes to also capture*

[3] For a definition of almost first degree of stochastic dominance see Anderson et al. (1989).

the uncertainty about the choice of the stochastic process? This is what will be discussed in this paper.

In the following, the option value of waiting under scientific uncertainty as illustrated in quadrant III of figure 1 will be derived using the difference between the geometric Brownian motion and the mean reverting process by applying contingent claim analysis. The results will be compared with those generated by either using a geometric Brownian motion or a mean-reverting process only. An example based on the decision problem whether or not to release herbicide tolerant rape seed in the EU will be used to illustrate the differences. The paper contributes to the suggestion made by Gilligan (ibid.) to further analyze the sensitivity of the results by Farrow et al. (ibid.) and Wesseler (ibid.), provides insights about the magnitude of error that can be made by choosing the wrong process, provides a solution to the problem and highlights the implication for the decision of whether or not to release transgenic crops.

2. The Option Value Under Scientific Uncertainty

The full value of owning the right to release a specific transgenic crop, $F(B,t)$, depends on the incremental net-benefits B from releasing the transgenic crop. Exercising the option to release provides a benefit stream $\pi(B,t)$ to the holder of the right[4] and produces not only irreversible costs but also irreversible benefits as discussed in detail in Wesseler (2002). The owner of the option, the decision maker, likes to know the value of the option and if to exercise immediately that is allowing releasing the transgenic crop for planting. Let's also assume the decision maker likes to release the transgenic crops without bearing any economic risk. By replicating the uncertain returns with known values from the market will derive the riskless value of the option to release transgenic crops. This is one of the basic insights of real option theory.[5] As Fisher (2000) has demonstrated this is equivalent to the quasi-option approach in environmental economics by Arrow and Fisher (1974) and Henry (1974) and further developed by Fisher and Hanemann (1986) and Hanemann (1989).

If it is assumed that the incremental net-benefits B of releasing transgenic crops follow a mean reverting process, they should be released immediately if B is greater than the identified hurdle rate for a mean reverting process B^*_{MR}. As B may also follow a geometric Brownian motion that dominates the mean reverting process the additional uncertainty of the difference between the two stochastic processes, the scientific uncertainty, B^*_{SU}, can be added, resulting in a hurdle rate B^*_{MR+SU}:

$$B^*_{MR+SU} = B^*_{MR} \cdot B^*_{SU} \tag{1}$$

The hurdle for transgenic crops under a mean-reverting process has been identified and discussed already elsewhere (e.g. Wesseler, 2002). Now, the steps to derive the real option value under scientific uncertainty and hence the hurdle for scientific uncertainty will be presented. Following Dixit and Pindyck (1994, pp. 20-21) a portfolio can be constructed that replicates the risk of releasing transgenic crops which consists of n units of incremental net-benefits from transgenic crops, nB, and one Euro invested in a riskless asset. If this portfolio will be hold over a short time interval, dt, the value of the portfolio will change depending on the rate of return, r, of the riskless asset and the change in value of nB. The change in value of nB may pay a dividend, δ, from holding it over the short time interval $n\delta Bdt$ and an uncertain return

[4] Think, e.g., of the EU-commission acting as the representative of EU citizens, similar to the manager of a private company acting on behalf of the stock owners.

[5] The seminal book by Dixit and Pindyck (1994) demonstrate the wide application possibilities of the real option approach. Nobel laureate Robert C. Merton (1998) provides an overview of the application

ndB. *dB* follows a process which is the difference between a geometric Brownian process and a mean reverting process, where the geometric Brownian process dominates the mean reverting process by FSD:

$$dB = \alpha B dt + \tilde{\sigma} B dz - \eta\left(\overline{B} - B\right) B dt - \overline{\sigma} B dz \qquad (2)$$

with B: incremental net-benefits of transgenic crops,

α: growth rate of incremental benefits assuming geometric Brownian motion,

$\tilde{\sigma}$: variance rate of the geometric Brownian motion,

η: speed of reversion,

$\overline{\sigma}$: variance rate of the mean-reversion process,

$\overline{B}$: reversion level,

dz: Wiener process

The expected value of a percentage change in incremental net-benefits over a short time interval is $\alpha - \eta\left(\overline{B} - B\right)$ which is not constant as it depends on *B* which fluctuates stochastically. Therefore, as *B* has to provide an expected rate of return equal to the risk adjusted rare of return, μ, derived from the capital asset pricing model as otherwise it would be more economically to reallocate investments, the expected return of the investment has to equal $\mu = \alpha - \eta\left(\overline{B} - B\right) + \delta$ and hence δ depends on *B*, $\delta(B) = \mu - \alpha + \eta\left(\overline{B} - B\right)$ (Dixit and Pindyck 1994, 147-150).

The return per Euro invested in the whole portfolio is:

$$\frac{r + n\sigma dB}{1 + nB} = \frac{r + n\delta B dt + n\left(\alpha B dt + \tilde{\sigma} B dz - \eta\left(\overline{B} - B\right) B dt - \overline{\sigma} B dz\right)}{1 + nB}$$

This can be rearranged to provide:

$$\frac{r + n\left(\alpha - \eta\left(\overline{B} - B\right) + \delta\right) B}{1 + nB} dt + \frac{nB\left(\tilde{\sigma} - \overline{\sigma}\right)}{1 + nB} dz \,. \qquad (3)$$

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of option pricing theory outside financial economics. The book by Amram and Kulatilaka (1999)

The first part of equation 3 is certain while the second part is uncertain. To simplify the notation we write $\sigma B dz = \tilde{\sigma} B dz - \overline{\sigma} B dz$. This portfolio can be compared with planting transgenic crops instead of buying them. Planting transgenic crops means exercising the option and hence, costs *F(B,t).* Exercising the option provides immediate incremental net-benefits $\pi(B,t)dt$. At the time of release this benefits are known with certainty over the short time interval *dt*. Also, the value of the option to release transgenic crops changes over the time interval *dt*. This random change can be calculated by applying Ito's Lemma:

$$dF = \left[F_t + \left(\alpha - \eta\left(\overline{B} - B \right)\right) B F_B + \frac{1}{2} \sigma^2 B^2 F_{BB} \right] dt + \sigma B F_B dz \, .$$

The return per Euro invested than is:

$$\frac{\pi dt + dF}{F} = \frac{\pi + \left[F_t + \left(\alpha - \eta\left(\overline{B} - B \right)\right) B F_B + \frac{1}{2} \sigma^2 B^2 F_{BB} \right]}{F} dt + \frac{\sigma B F_B}{F} dz \, . \tag{4}$$

As the portfolio should replicate the risk of releasing transgenic crops, the uncertain part of the portfolio has to be equal to the uncertain part of the returns from releasing them:

$$\frac{nB\sigma}{1 + nB} dz = \frac{\sigma B F_B}{F} dz \, . \tag{5}$$

The arbitrage pricing principle says that two assets in the market with the same risk have to have the same value. If the same line of thinking will be applied, than also the certain return of the portfolio and the certain return from the release of transgenic crops have to be the same:

$$\frac{r + n\left(\alpha - \eta\left(\overline{B} - B \right) + \delta \right) B}{1 + nB} dt = \frac{\pi + F_t + \left(\alpha - \eta\left(\overline{B} - B \right)\right) B F_B + \frac{1}{2} \sigma^2 B^2 F_{BB}}{F} dt \, . \tag{6}$$

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includes several case studies of real option pricing.

If $nB/(1+nB)$ is substituted on the right-hand side by $\frac{BF_B}{F}dz$ from equation 4 and δ substituted by $\mu - \alpha + \eta\left(\overline{B} - B\right)$, equation 5 can be rearranged to provide:

$$\frac{1}{2}\sigma^2 B^2 F_{BB} + \left(r - \mu + \alpha - \eta\left(\overline{B} - B\right)\right)BF_B - rF + \pi = 0\,. \tag{7}$$

The term F_t dropped as an infinite stream of returns from transgenic crops is assumed if once released. The boundary conditions for the differential equation 7 are the well-known 'value matching' (equation 9) and the 'smooth pasting' (equation 10) conditions and that the value of the option to release transgenic crops has no value if there are no incremental net-benefits (equation 8):

$$F(0) = 0 \tag{8}$$

$$F(B^*) = B^* - I + R \tag{9}$$

$$F'(B^*) = B'^*\,. \tag{10}$$

A solution to the differential equation 7 and hence, the value of the option, can be found by defining a function of the form:

$$F(B) = AB^\theta h(B), \tag{11}$$

where A and θ are constants that have to be chosen to solve equation 7. Following the steps provided by Dixit and Pindyck (1994, 162-163), first equation 11 will be substituted in equation 6. After rearrangement:

$$\begin{aligned} &B^\theta h\left[\frac{1}{2}\sigma^2\theta(\theta - 1) + \left(r - \mu + \alpha - \eta\overline{B}\right)\theta - r\right] + \\ &B^{\theta+1}\left[\frac{1}{2}\sigma^2 Bh_{BB} + \left(\sigma^2\theta + r - \mu + \alpha - \eta\overline{B} + \eta B\right)h_B + \eta\theta h\right] = 0. \end{aligned} \tag{12}$$

Second, the terms in brackets both have to be equal to zero. The first bracketed term is a quadratic equation. As one of the boundary conditions is $F(0) = 0$, only the positive solutions will be considered. Solving the quadratic equation provides the following solution for θ:

$$\theta = \frac{1}{2} + \frac{(\mu - r - \alpha + \eta\overline{B})}{\sigma^2} + \sqrt{\left[\frac{r - \mu + \alpha - \eta\overline{B}}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2r}{\sigma^2}} \tag{13}$$

Third, the second bracketed term can be transformed into a hypergeometric differential equation by the substitutions $x = \frac{-2\eta B}{\sigma^2}$, $h(B) = g(x)$, $h_B = \frac{-2\eta B}{\sigma^2} g_x$, $h_{BB} = \left(\frac{-2\eta B}{\sigma^2}\right)^2 g_{xx}$:

$$x g_{xx} + (b - x) g_x - \theta g = 0 \tag{14}$$

where

$$b = 2\theta + 2(r - \mu + \alpha - \eta\overline{B})/\sigma^2$$

Fourth, the solution to equation 14 is the confluent hypergeometric function $H(x;\theta,b)$ (see Dixit and Pindyck 1994, p.163) which results in the following solution to equation 6[6]:

$$F(B) = AB^{\theta} H\left(\frac{-2\eta B}{\sigma^2};\theta,b\right) \tag{15}$$

The values for A and the critical value B^* where the release could be justified can be found numerically using the two remaining boundary conditions $F(B^*) = B^*-I+R$ and $F_B(B) = 1$.

3. Application of the model

The growth rate α and the variance rate $\tilde{\sigma}$ were estimated by computing the maximum likelihood estimator assuming continuous growth (Campbell et al., 1997,

[6] Note the difference to the result provided by Dixit and Pindyck for a mean-reverting process, where x is positive.

Chapter 9.3). The estimators for α and $\tilde{\sigma}$ in closed form for annual returns, *g*, over *t* = *n* years are:

$$\hat{\alpha} = \frac{1}{n}\sum_{t=1}^{n} ln\left(\frac{g_t}{g_{t-1}}\right) \tag{16}$$

$$\hat{\tilde{\sigma}} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(\left(ln\left(g_t/g_{t-1}\right) - \hat{a}\right)\right)^2} \tag{17}$$

The estimators for the mean reverting process are $\hat{\bar{g}} = -\hat{a}/\hat{b}$, $\hat{\eta} = -ln\left(1+\hat{b}\right)$, and $\hat{\bar{\sigma}} = \hat{\bar{\sigma}}_{\varepsilon}\sqrt{\frac{ln\left(1+\hat{b}\right)}{\left(1+\hat{b}\right)^2 - 1}}$, where $\hat{a}$ and $\hat{b}$ are estimators of the linear regression $ln\ \left(g_t/g_{t-1}\right) = a + b\ g_{t-1} + \varepsilon_t$ and $\hat{\bar{\sigma}}_{\varepsilon}$ is the standard error of the regression. a and b are substitutes for

$$a = \bar{g}\left(1 - e^{-\eta}\right) \tag{18}$$

$$b = \left(e^{-\eta} - 1\right)g_{t-1} \tag{19}$$

of a first order autoregressive process (AR(1)) with a normally distributed error term with mean zero and variance $\bar{\sigma}_{\varepsilon}^2 = \frac{\bar{\sigma}^2}{2\eta}\left(1 - e^{-2\eta}\right)$.

The same estimators can be used for the parameters of the combined process of equation 1. *dB* can be decomposed in $dB = dB_{BM} - dB_{MR..}$

The parameters to calculate the different hurdle rates will be estimated from FAO time series data for rape seed in France. Rape seed was chosen as herbicide tolerant seed varieties exist that show a high adoption rate in the United States and can be expected to be technically suitable for France as well where rape seed is grown on a large scale. The average return per hectare for rape seed in France over the period 1970 to 1995 are provided by FAO (2002). As the FAO statistics provide only nominal prices, the data were transferred into real prices in US dollar (USD) using the

United States Department of Agriculture (Shane, 2000) real exchange rates for rape seed. The data to estimate the mean-reverting process have been scaled down by dividing the annual gross revenue from rape seed by the estimated long-run average level, which was estimated to be about 5510 USD per hectare. These data have been used for the estimation of the parameter values shown in table 1 and table 2.

In addition to the estimated parameter values the risk free interest rate, r, is assumed to be about 4.5%, which is equivalent to the interest rate at the European Central Bank for the month of December 2000. The risk adjusted rate of return μ is assumed to be 8%. For simplicity it is also assumed that the net irreversible costs $I - R = 1$.

In the case of rape seed the immediate incremental net-benefits are about 32% if the results from Canada are applied to the EU (Serecon Management Consulting Inc. and Koch Paul Associates, 2001, Table 4.4). In this case modeling incremental net-benefits B by a mean reversion process would result in a hurdle rate of B^*_{MR} = 1.296 and passed by B = 1.32. The value of scientific uncertainty with 1.009 is low and increases the hurdle rate to about B^*_{MR+SU} = 1.308, which will also be passed by B. If a geometric Brownian motion would be assumed the hurdle rate would be B^*_{GB} = 2.43 and not be passed. Ignoring the scientific uncertainty about the underlying stochastic process would in this case result in the wrong decision to not release transgenic crops, if a geometric Brownian motion would be assumed.

Table 1. Parameter estimations for the geometric Brownian motion and the mean reverting process.

Geometric Brownian motion	Mean reverting process
$\hat{\alpha} = 0.0473$	$\hat{a} = 0.2635$
$\hat{\hat{\sigma}} = 0.2871$	$\hat{b} = -0.2635$
	$\hat{\hat{\sigma}}_{\varepsilon} = 0.2728$
	$\hat{\eta} = 0.3059$
	$\hat{\hat{\sigma}} = 0.1824$

Table 2. Parameter values chosen for the calculation of immediate minimum benefits B^*

Parameter (annual)	Value	Source
growth rate $\hat{\alpha}$	0.047	FAO (2002)
risk-free rate of return r	0.045	European Central Bank, Dec. 2000
standard deviation $\hat{\hat{\sigma}}$	0.287	FAO (2002)
risk adjusted rate of return, μ	0.080	assumed
convenience yield, δ	0.033	$(\mu\text{-}\hat{\alpha})$
β	1.453	equation (9)
$\beta/(\beta-1)$	3.207	
B^* assuming I – R = 1	2.429	geometric Brownian motion
	1.296	mean reverting process
	1.009	scientific uncertainty
	1.308	including scientific uncertainty

4. Conclusion

In this paper we have addressed the problem of scientific uncertainty defined as the problem of identifying the correct stochastic process of incremental net-benefits from transgenic crops. Combining a mean reversion and geometric Brownian process reduced the problem of scientific uncertainty. An application of the approach to the release of rape seed indicated only a small impact of scientific uncertainty. Ignoring scientific uncertainty on the other hand may lead to a wrong decision. It still has to be shown if that in general is the case.

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