Valuing Clean Development with Emission Credit Price Uncertainty: A Real Option Analysis for A/R CDM Project in Indonesia

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Abstract

There are growing intrests in CDM (Clean Development Mechanism) project using afforestation or reforestation as an effective measure to control the greenhouse gases. Typical problems associated with A/R CDM projects are the stochastic price of emission credits (CER) and the renewal decision of A/R CDM after its expiry of the operation period. This paper presents an investment model to analyze the economic feasibility of A/R CDM project while considering CER price uncertainty and project renewal decision. Our analysis derives numerically explicit conditions under which A/R CDM projects provide sufficient returns in the presence of CER price uncertainty and investment irreversibility. For practical consideration of the model, A/R CDM project in Indonesia is studied.

Keywords: real option, A/R CDM, uncertainty

1 Introduction

Under the Kyoto Protocol which was entered into force in 2005 to regulate greenhouse gases, several flexible mechanisms are allowed for compliance schemes. Among others, there are growing interests in the Clean Development Mechanism (CDM) that is project-based. CDM project enables the so-called Annex 1 countries to carry out emission-reducing investment in developing countries by providing financial benefits in a form of emission credits. Due to irreversible path of currently ongoing global warming, it is important for mankind to enhance adaptability of climate change through the channels of CDM projects. Forest sector may provide unique opportunities to promote synergy between mitigation and adaptation.[1] In particular, the land use, land-use change and forestry (LULUCF) activities through afforestation and reforestation projects, known as A/R CDM (Afforestation/Reforestation Clean Development Mechanism), is expected to provide significant opportunity to mitigate climate change.

Adopting CDM mechanism into the forest sector dates back to the Conference of Parties 3 (COP3), the Kyoto conference on climate change, where there was a concord that forest activities limited to afforestation and reforestation are eligible for the CDM. The crediting period for a A/R CDM project activity is selected by the project participants and may be either a twenty-year crediting period which may be renewed at most two times or a single thirty-year crediting period. In contrast to CERs generated by energy and other emission reduction projects, CERs from A/R CDM projects are of limited validity due to its non-permanent nature as a sink. Forestry projects mitigate climate change as long as the carbon remains stored in the vegetation and soil. However, forest sinks are potentially reversible due to disturbances such as fires or conversion of forest land back to pasture land, for example, which causes the carbon to be released back to atmosphere, and reverses the climate benefit. For this reason, the regulations of the CDM define the credits from forestry projects as short-term credits, tCERs (temporary Certified Emission Reductions), and long-term credits, lCERs (long-term Certified Emission Reductions, according to different durations of validity. Both tCERs and lCERs are of temporary nature and have to be replaced upon expiry. tCERs are valid for one commitment period of five

[1] Global efforts to cope with climate change include two basic response; mitigation and adaptation. Mitigation is defined as an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases. Adaptation is adjustment in natural or human systems in response to actual or expected climatic stimuli and their impacts on natural and socio-economic systems, which moderates harm or exploits beneficial opportunities (IPCC 2002).

years, which means that credits for existing carbon stocks are re-issued after each verification event. If the carbon stock or part of it has been lost in the meantime, the next verification will simply yield less tCERs than before. tCERs cannot be banked and have to be used in the commitment period in which they are issued. At expiry, one unit of tCER has to be replaced by an AAU, a permanent CER, an ERU, a RMU or by another tCER; it cannot be replaced by an lCER. Conversely, credits for projects generating lCERs are valid until the end of the project's crediting period. lCERs are treated as valid until the end of project's crediting period. At expiry, one unit of lCER has to be replaced by an AAU, a permanent CER, an ERU, or a RMU. It is impossible to replace an lCER with a tCER or another lCER.

Countries have entered into formal negotiations on a climate change agreement after 2012 when the Kyoto Protocol's first commitment period ends. There is considerable uncertainty as to what this post-2012 regime will look like and what market instruments and mechanisms will be employed within this. The CDM, including A/R CDM, has become one of the most important elements of the Kyoto Protocol, but has also been criticized for various reasons. This includes a lack of transparency, inadequate governance structures, cumbersome procedures, poor environmental integrity, little contribution to sustainable development, an inadequate geographical distribution of CDM projects, its limited ability to reduce greenhouse gas emissions in some sectors and having the character of an offsetting mechanism. However, from the point that most of the international climate discussions on expanded or new market mechanisms in a post-2012 regime are focused on the supply of credits credits from developing countries and there is some belief that the experience of the CDM has demonstrated its power as a tool to engage developing countries in mitigation activities, we can expect that with some trepidation, greenhouse gas emissions trading and the project-based mechanisms including the CDM under the Kyoto Protocol will last for the period after 2012 with possible improvement and in this way, the role of forest carbon sinks will be expanded including other LULUCF activities, for example, reducing greenhouse gas emissions from deforestation and forest degradation, restoration of wetlands, sustainable forest management and other sustainable land management activities, as well as afforestation and reforestation or A/R.

Reflecting such a gaining importance about the role of forests as carbon sinks, the forestry literatures are actively integrating the influence of the role of carbon management in forests with optimal harvesting decision problem in economic perspective. Balteiro and Rodriquez(2006) determined, using a dynamic programming, the optimal coppice management regimes of Eucalyptus in Brazil and Spain. Chladna(2007) extended the analysis of the optimal rotation period by considering uncertain revenue streams from carbon trading in a stochastic setting. Specifically, Chladna(2007) developed a real options model given uncertainties in the future wood and CO2 price behaviour, following Ornstein-Uhlenbeck mean-reverting process and the geometric Brownian motion(GBM) process respectively. Considering only discrete two actions, that is, postpone the harvest or harvest and sell the land, Chladna(2007) found that optimal rotation periods vary considerably with the type of price process, the way how carbon income is defined, and the selection of discount rates. Olschewski and Benitez(2009), based on Faustmann(1849) and Haryman(1976), aimed at determining the impact of a joint production of timber and carbon sequestration on the optimal rotation of a fast-growing species in north-western Ecuador. Olschewski and Benitez(2009) concluded that in contrast to an optimum of 15 years when focusing on timber production only, joint production leads to a doubling of the rotation length, which means that timber harvest should be postponed until the end of the carbon project. However, this result is based on the assumption that future carbon prices will remain constant.

In Korea, economic study on forest field is still in infancy, while Park et al.(2007) studied the economic feasibility of industrial forest plantations and A/R CDM project in Indonesia applying the method of net present value (NPV), internal rate of return (IRR), and B/C ratio (Benefit/Cost ratio).

Park et al.(2007) concluded that based on their scenarios, A/R CDM project couldn't secure economic feasibility representing negative value of NPV as well as that of B/C ratio less than 1. However, it has shown that the traditional net present value rule, even though it has been referred virtually every besiness sector, can give somewhat wrong answers, since it ignores irreversibility and the option of delaying an investment (Dixit and Pindyck, 1994). In most cases, investment decisions are made in an uncertain environment and are costly to reverse later. Clearly, central aspects of investing in A/R CDM projects are the presence of irreversibility and uncertainty. Investment in A/R CDM projects requires enormous amount of initial funds, for building production infra and establishing capital goods, which is at least partially sunk. Also, the price of CER fluctuates reflecting uncertainties induced from various factors of market. In such a world, the firm investing in A/R CDM projects must make a decision with great deliberation, considering diverse betefit and cost factors concretely.

In this paper, we aim to present the optimal investment decision model in A/R CDM projects, explicitly accounting for features of uncertainty and irreversibility. When the uncertainty exists in the market, the firm implicitly possesses an option to invest optimally. This option has value, hence making the investment is like exercising the call option, and the cost of the investment is the strike price of the option. Through the next section, we describe our treatment of uncertainty in more detail and set forth the model. In this model, the spot price of the CER follows a stochastic process, and it is costly to exercise an option. The solution to this model is obtained, and in section 3, we conduct a simulation analysis. In performing the numerical exercises, we consider an A/R CDM project in Indonesia as a specific example. We offer some concluding remarks in section 4.

2 The Model

It is assumed that uncertainty in the model is largely associated with emission credit price. There may be other uncertainty factors related to emission-reducing projects. For example, technological progress in the field of carbon-capture and storage may provide greater possibility to lower price of emission credit but its possibility is not fully known in advance. Based on efficient market for emission tradings, such uncertainty and related information are reflected into the price of emission credits, i.e., CER. Since most of firms which undertook afforestation or reforestation CDM projects have chosen lCER so far, the model in the paper restricts to a long-term CDM project with 20 years of expiry. We consider the lCER price $p(t)$ evolves exogenously over time following a geometric Brownian motion, which is the continuous-time formulation of the random walk:

$$dp(t) = \alpha p(t)\, dt + \sigma p(t)\, dz. \tag{1}$$

where dz is the increment of standard Wiener process, uncorrelated across time, with $E(dz) = 0$ and $Var(dz) = dt$. It is assumed that the drift parameter α and the volatility parameter σ are time invariant. By the standard theory of Brownian motion, we know that $\ln p_t$ is normally distributed with mean $\ln p_0 + (\alpha - 0.5\sigma^2)t$ and variance $\sigma^2 t$. That is, uncertainty about the future price of CER increases over time. The firm is risk neutral and maximizes the sum of its expected net present value of profits and the salvage value upon the expiry date while considering uncertainty of lCER price as well as the option of the project renewal. Let $V(p)$ be the optimal value function for a firm investing in A/R CDM project at instant t. The optimal value function of the firm investing in A/R CDM project with a twenty-year crediting period can be specified as,[2]

$$V(p) = \max E \int_0^T (p-c)Qe^{-rt}dt + \max\left[(V_2 - R)\, e^{-rT}, 0\right] \qquad (2)$$

where $(p-c)Q$ is profit of the firm, r is the discount rate, and V_2 is the present value of the A/R CDM for the extended additional 20 years after T. R denotes the renewal cost of A/R CDM which accounts for the opportunity cost of the trees as timbers. The maximization is subject to equation (1) for $V(p)$. The value of $\max\left[(V_2 - R)\, e^{-rT}, 0\right]$ is interpreted as an European call option value that is determined using the Black-Scholes formula. Since the Black-Scholes model assumes that the option can be exercised only at expiration, it offers simple but effective frame for the analysis. Because many topics covered in real options allow investors to exercise their options at any point during the life of contract, analysis based on Black-Scholes model leads to fallacies. However, since A/R CDM project with a twenty-year crediting period is suitable for the Black-Scholes approach for that there is an exact expiration date at which participants must decide whether they continue furthermore after the first T years or make exits from the CDM business.

The firm investing in A/R CDM project must find an optimal investment threshold π^* at which it is optimal for the investment. Profits lower than π^* do not induce investment due to sufficiently low profits in the presence of uncertainty. Denoting $V_1(p)$ as the value function for the first 20 period, dynamic programming yields the following Bellman equation

$$rV_1(p) = \max\left((p-c)Q + \frac{1}{dt}EdV_1(p)\right). \qquad (3)$$

By making use of Ito's Lemma, we expand $dV_1(p)$ as $dV_1(p) = V_{1,p}(p)dp + \frac{1}{2}V_{1,pp}(p)dp^2$. Then, substituting this expression into equation (3), and noting that $dt^2 \to 0$, $dtdz \to 0$, $E(dz) = 0$, $dz^2 = Var(dz) = dt$, we obtain the

[2] Present model does not consider the biological growth of the timbers which must be an important factor in determining each period's revenue from the A/R CDM. However, the specific tree type considered in current anlaysis, Acacia mangium, is one of the major fast-growing tree used in forest plantation. Due to its rapid growth and tolerance of poor soil condition, we assume that the CER revenue is created from the fifth years of the business.

following HJB equation (Hamilton-Jacobi-Bellman equation).

$$rV_1(p) = (p-c)Q + \alpha p V_{1,p} + \frac{1}{2}\sigma^2 p^2 V_{1,pp}. \tag{4}$$

Since the equation (4) is the second-order linear equation in p, applying a standard approach as in Dixit and Pindyck(1994) yields the following solution for the non-homogeneous part of the equation (4):

$$V_1(p) = \left(\frac{pQ}{r-\alpha} - \frac{cQ}{r}\right)\left(1 - e^{-rT}\right) \tag{5}$$

where the RHS term represents the present value of net revenue of lCER income with the expiry date T given. The investment option is derived from the homogeneous part of equation (4): $F(p) = Ap^{\beta}$ where β is the positive root of the characteristic equation specified as

$$\beta = \frac{1}{2} - \frac{\alpha}{\sigma^2} + \sqrt{\left(\frac{\alpha}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}. \tag{6}$$

It remains to determine the critical lCER threshold p^*. The lCER price higher than p^* triggers investment, and the firm is willing to pay (at least partially) irreversible expense of initial sunk cost K to exercise the investment option. Following two boundary conditions ensure the optimality of p^*:

$$A_1 {p^*}^{\beta_1} = \left(\frac{p^*Q}{r-\alpha} - \frac{cQ}{r}\right)(1 - e^{-rT}) + \widetilde{C}e^{-rT} - K \tag{7}$$

$$\beta_1 A_1 {p^*}^{\beta_1 - 1} = \frac{Q}{r-\alpha}(1 - e^{-rT}). \tag{8}$$

$\widetilde{C}$ denotes the European call option value derived from $\max\left[(V_2 - R)\, e^{-rT}, 0\right]$ in the equation (2):

$$\begin{aligned}
\widetilde{C} &= v_2 N(d_1) - Re^{-r(T-t)} N(d_2) \\
d_1 &= \frac{\ln(v_2/R) + \left(r + \sigma^2/2\right)(T-t)}{\sigma\sqrt{T-t}} \\
d_2 &= \frac{\ln(v_2/R) + \left(r - \sigma^2/2\right)(T-t)}{\sigma\sqrt{T-t}} = d_1 - \sigma\sqrt{T-t}
\end{aligned}$$

v_2 denotes the present value of A/R CDM project in the renewal period. Equations (7) and (8) represent the value-matching and the smooth-pasting conditions, respectively. At the critical threshold p^*, it is optimal for the firm to exercise the option to invest in the A/R CDM project at the initial sunk cost K. The value-matching condition requires that the net benefit obtained by investment must offset the investment option value. In addition, the solutions must also satisfy the smooth-pasting condition. The smooth-pasting condition requires that a marginal benefit of the project with respect to lCER price has the same value with that from the investment option. Hence, the smooth-pasting condition guarantees a smooth-transition between two domains, bordered by the optimal investment threshold p^*. If the marginal value of investment option surpasses that of the operating A/R CDM project, it is not optimal to exercise the option because of the presence of positive waiting value which is equivalent to $Q(1-e^{-rT})/(r-\alpha) - \beta_1 A_1 p^{*\beta_1 - 1}$. At p^*, the waiting value vanishes to 0. By solving (7) and (8) simultaneously, we identify the critical point p^*:

$$p^* = \left(K + \frac{cQ}{r}(1-e^{-rT}) - N(d_1)e^{-rT}\right) / \left(\frac{Q}{r-\alpha}(1-e^{-rT})\frac{\beta-1}{\beta}\right). \quad (9)$$

The term $(\beta-1)/\beta$ represents hysteresis. The term $N(d_1)\, e^{-rT}$ is derived from the so-called greek delta of the Black-Sholes. The term $cQ(1-e^{-rT})/r$ is interpreted as the variable maintenance cost of CDM discounted by $r/(1-e^{-rT})$. As is consistent with the conventional real option literature, p^* is increasing in the costs, i.e., K, c whereas decreasing in the salvage values.

3 Numerical Example : The Indonesia Case

3.1 Data

Numerically solving the system facilitate the obtainment of more detailed insights concerning the relation between the critical values p^* and other parameters. As noted previously, an A/R CDM project in Indonesia is considered. In 2006, the Forest Service of the Korea signed a memorandum of understanding (MOU) with the Ministry of Forestry of Indonesia concerning the cooperation on investment in 500,000ha of industrial forest plantation and on A/R CDM projects in Indonesia. A set of central values for the parameters for the numerical analysis are imported from Park et al.(2007)

Parameter	Value
the drift rate (α)	0.00024
the volatility rate (σ)	0.027
the risk-free interest rate (r)	0.05
β_1	11.88
the crediting period (T)	20years
the current value of the expected net benefit (P_0)	15,457,537dollars
the sunk cost (the initial investment cost, K)	18,779,380dollars
the cost per unit of emission permit (c)	16dollars
Total emission permits gained (Q)	3,854,400CER
the Black-Scholes call option value ($\widetilde{C}$)	2,381,699dollars
the investment area	12,000ha
the kind of timber	Acacia mangium
the growth rate of timber	25m^3/ha

Table 1: Parameter values for simulations

which studied the economic feasibility of industrial forest plantations and A/R CDM project in Indonesia by applying the traditional NPV approach. Monetary unit are converted to the dollar using the average Korean won-dollar exchange rate in 2009, i.e., 1276.4won/dollar.

To estimate the drift parameter α and the volatility parameter β, let $y(t) = \log(p(t)) - \log(p(t-1))$. Then, when $p(t)$ evolves the geometric Brownian motion, $y(t)$ has a normal distrinution with mean $\left(\alpha - \sigma^2/2\right)\Delta$ and variance $\sigma^2\Delta$, where Δ represents the time inverval. The drift parameter and the volatility parameter are derived from $\frac{\overline{y}}{\Delta} + \frac{s_y^2}{2\Delta}$, and $\frac{s_y}{\sqrt{\Delta}}$, respectively, where $\overline{y} = \sum_{t=1}^{T} y(t)/T$, and $s_y = \sqrt{\sum_{t=1}^{T}(y_t - \overline{y})^2/(T-1)}$. The daily CER price data ranged from 13 August 2007 to 9 september 2009 are provided by the Point Carbon and the lCER prices are 60% discounted compared to CER price in non-forest CDMs (Olschewski and Benitez, 2005). The results are $\alpha = 0.00024$ and $\sigma = 0.027$. As a central case, we take the risk-free interest rate $r = 0.05$. In following section, we vary r from 0.03 to 0.09, performing the sensitivity analysis. The parameter β is 11.88 and we know $T = 20$ since the A/R CDM project of twenty-year crediting period is considered. From Park et al.(2007), we apply $\hat{S}$, the discounted value of expected net benefit during the crediting period, of 15,457,537dollar, the initial sunk cost K of 18,779,380dollar, and the cost per unit of emission permit c of 16dollar. The investment area and the selection of timber type were followed by the criteria from the Ministry of Forestry of Indonesia. Under Indonesian law, there is no legal restriction for foreign investors to grow Acacia mangium in A/R CDM project as well as ample technology accumulation is in formation needed for silviculture. Since the economic final age of Acacia mangium is 8~15 years and its annual average growth rate is 25m^3/ha, we designed that Acacia mangium grows up at a rate of 25m^3/ha per year, for 8 years. In addition, because Acacia mangium yields 1.606 tCO_2/m^3, we get $Q = 3,854,400$. Finally, we use the Black-Scholes formula to obtain $\widetilde{C}e^{-rT} = 2,381,698$.

3.2 Empirical Analysis

In the central case of parameter values, we found the optimal investment threshold p^*, the critical price level which induces invertors to exercise their options is derived as about $17.75 dollars. Meanwhile, we see that the recent CER price fluctuates at the level of 12~14 euros, which can be converted to 16.74~19.53 dollars, based on the average exchange rate 1.3953 in 2009. Based on the our construction of the model, hence, the result shows that to any extent the A/R CDM project in Indonesia does not satisfy its economic feasibility. Since our model is only allowing for price uncertainty, even higher threshold price level would be needed to insure against various risk factors such as risk of CER delivery. In addition, for example, political and commercial risks related with developing countries should be considered. Neverthless, if we expect that the price level of emission permits would move upwards followed by imposition of reduction liability and/or consolidated reduction efforts under Post-2012 scheme, investment option value in A/R CDM business may still exists. In the following, we consider the impacts of variation in parameters upon the critical price behavior.

Figure 1 shows the effects of changes in the risk-free interest rate r and the volatility rate σ^2 on p^*. Increasing σ^2 reflects the growing price uncertainty, as wall as the raising waiting value. Hence, we expect that an increase of σ^2 will lessen the investor's incentive, moving up the optimal threshold level. Coinciding with the intuition, Figure 1 displays the positive association of p^* with σ^2. On the other hand, as r increases, p^* is lowered. Figure 2 through Figure 4 show that the initial investment cost K corresponding the sunk cost has a positive effect on p^*. Larger K increases the level of p^*, inducing the investors behave in a more conservative way. It is plausible from the point of view that K acts as an opportunity cost to the participants, since an investment in the A/R CDM project is at least partially irreversible. However, in our simulation, the effect of K is not much sensitive compared to variable annual maintenance cost c, implying that efforts of reducing variable cost would be more effective in inducing earlier investment. Finally, the effect of interest rate on p^* is ambiguous, depending on impacts of several parameters employed.

Insert Figure 1. Sensitivity of p^* to r and σ^2

Insert Figure 2. Sensitivity of p^* to K

Insert Figure 3. Sensitivity of p^* to c

Insert Figure 4. Sensitivity of p^* to K and c

4 Conclusion

As a landmark international treaty, the Kyoto Protocol being entered into force in February 2005, countries are undertaking their full-scale efforts for reducing greenhouse gas emissions. With this the role of forest carbon sinks are drawing attentions of the world, since it makes both mitigation and adaptation possible, the two basic response for addresing climate change. Reflecting such a gaining importance about the role of forests as a carbon sinks, worldwide forestry literatures are actively integrating the influence of the role of carbon management in forests with optimal harvesting decision problem in economic perspective. However, in Korea, economic study on forest field is still in infancy, while Park et al.(2007) performed the study on the economic feasibility of industrial forest plantations and A/R CDM project in Indonesia using the method of NPV, IRR, and B/C ratio, and conclued that A/R CDM project couldn't procured its economic feasibility since it displayed negative net present value, and B/C ratio less than 1. The traditional analysis about economic feasibility, however, ignores irreversibility and the option of delaying an investment and sometimes misleads investors, giving very wrong answers, since we are living in era of uncertainty.

In this paper, we represent the optimal investment decision model in A/R CDM projects, explicitly accounting for features of uncertainty and irreversibility based on the real option theory. Following the standard setting in real options, we describe the uncertainty by assuming that the uncertainty arises from the CER price, evolving exogenously over time as a geometric Brownian motion. This is reasonable in that generally the market price reflects various uncertainty factors raised in the market. We also represent numerical example, since numerically solving the system promotes the obtainment of more detailed insignts about the model. As an example, we consider an A/R CDM project in Indonesia, some parameter values were refered from Park et al.(2007) and the daily CER price data, from 13 August 2007 to 9 september 2009, was acquired from the Point Carbon.

Our analysis shows that in the central case of parameter values the optimal investment threshold p^* is derived as about \$17.39. Considering that the recent CER price fluctuating at the level of 12~14 euros is generally much higher than the CER price in the A/R CDM, the result concludes that the A/R CDM project in Indenesia does not secure its economic feasibility. This is a partial proof for that there are few A/R CDM projects currently active in the world.

Since our model is only reflecting the price uncertainty, other various risk factors, like political risk and/or commercial risk are not considered, higher critical price level might be required to induce investors to participate in A/R CDM projects, enduring other various risks in real world. This does not mean A/R CDM project can be somewhat ignored by investors, due to its slightly lack of economic feasibility. When we expect that the imposition of reduction liability and reduction efforts will be consolidated under Post-2012, the price level of emission permits is anticipated to move upwards, the investment option value in A/R CDM industry still exists.

We also consider the impact of variation in parameters upon the critical price behavior. The sensitivity analysis shows the decreasing optimal investment threshold as r increases, which means that the investors gain more incentives to participate in A/R CDM projects as r increases. This is because the A/R CDM project considered in this paper terminates after 20 years, the investors rather decide to take part in the project hurriedly as r moves up than suppress themselves from exercising the options. Also, the optimal critical price level increases as the volatility rate σ^2 representing the price uncertainty moves up, coinciding with intuition. In addition, an incerease of cost factors K and c both delays investment while growing c has more sensitive hold-up effect.

Lastly, some major caveats need to be taken into account. There were certain issues that could not be addressed due to limited scope of the study. But these issues must be kept in mind while considering the implications of this paper in general. Firstly, for more realistic and generalized model construction, it is essential to integrate the biological growth function of timber. Also, as we mentioned, another major risk related to the developing countries is the political risk, and modelling of the political risk is anticipated to get significant and interesting implication. Further, in this paper, the price process was assumed to follow a non-stationary random walk process. There are many issues for price series, and in fact, the investment decisions under the uncertainty depend heavily on the timber price process assumed in the analysis.

5 References

Brown, S, Sathaye, J., Cannel, M., Kauppi, PE (1996), Mitigation of carbon emissions to the atmosphere by forest management, *Commomwealth Forest Review* 75(1):80-91.

Chladna, Z. (2007), Determination of optimal rotation period under stochastic wood and carbon prices, *Forest Policy and Economics* 9(8), 1031-1045.

Park, C., Kwon K., and Kim, S. (2007), An economic analysis of industrial forest plantation and A/R CDM project in Indonesia, *Journal of Korean Forest Society.*

Diaz-Balteiro, L., and Rodriquez, L.C.E. (2006), Optimal rotations on Eucalyptus plantations including carbon sequestration - A comparison of results in Brazil and Spain, *Forest Ecology and Management* 229(1-3), 247-258.

Dixit, A.K., and R.S. Pindyck (1994), *Investment under Uncertainty*, Princeton NJ: Princeton University Press.

IPCC (2002), Climate and biodiversity, IPCC technical paper V. Habiba G, Avelino S, Robert T (eds) Watson and David Jon Dokken, Intergovernmental Panel on Climate Change.

Olschewski, R., and Benitez, P.C. (2009), Optimizing joint production of timber and carbon sequestration of afforestation projects, *Journal of Forest Economics* 16(1), 1-10.

Olschewski, R., and Benitez, P.C. (2005), Secondary forests as temporary carbon sinks? The economic impact of accounting methods on reforestation projects in the tropics, *Ecological Economics* 55(3), 380-394.

Copeland, T. and Antilarov, V. (2001), *Real Options*, Texere.

Figure 1: Sensitivity of p^* to r and σ^2

Figure 2: Sensitivity of p^* to K

Figure 3: Sensitivity of p^* to c

Figure 4: Sensitivity of p^* to K and c