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Optimal Pricing of the Carbon Trading Market Based on a Demand-Supply Model

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Abstract

The Kyoto Protocol has clearly specified various methods and measures of reducing greenhouse gases, and the reduction of emissions using the land-use change and forestry (LUCF) methods has become legally enforced as well. Countries all over the world are actively developing their local emission trading mechanisms in hopes of aligning with those international standards. Among them, the carbon trading mechanism has been widely perceived by the world as an important economic instrument for reducing greenhouse gases. In this study, we first established a theoretical economic model of supply and demand for four carbon trading mechanisms, and then derived the optimal conditions to decide the optimal trading price and trading duration of carbon contract with endogenous and exogenous carbon prices.

Keywords: carbon trading contract, afforestation, carbon sequestration, afforestation on agricultural land, forest management

1. Introduction

In recent years, the increasing emission of greenhouse gases that lead to the global warming crisis has caught the world's attention. To response the issue, the Kyoto Protocol was adopted by the 3rd Conference of the Parties (COP3) in 1997, and entered into force on February 16, 2005. The Kyoto Protocol has clearly specified various methods and measures of reducing greenhouse gases, including (1) the introduction of Emission Trading (ET) between or within developed countries; (2) a Clean Development Mechanism (CDM) that facilitates reductions of greenhouse gas emissions jointly between the countries listed in Attachment 1 (mostly developed countries) and those not listed in Attachment 1; (3) Joint Implementation (JI), by which many countries in the European Union can collaborate in unity, where some countries cut back while some other countries increase their emissions, thereby reducing overall greenhouse gas emission on an aggregate level. These three methods are commonly referred to as Kyoto Mechanisms. The trading mechanism has been widely perceived by the world as an important economic instrument for reducing greenhouse gases; its transaction costs are also lower than CDM and JI[1]. Countries all over the world are actively developing their local emission trading mechanisms in hopes of aligning with the international standards.

Carbon sequestration policies have already been an abundance of regional trading activities among the world, while power companies and energy-intensive manufacturers are actively investing in green projects to provide credits for their emissions of carbon dioxide or other greenhouse gases (Cacho et al., 2003). It was stated in the Kyoto Protocol that during the first commitment period (2008-2012), the countries listed in Attachment 1 may utilize carbon sequestration through forests to deduct the amount of carbon emissions. Whether the carbon sequestration arising from the activities of land-use change and forestry (LUCF) (Watson et al., 2000) may be treated as credits for deducting greenhouse gas emissions has been still widely under debate among countries. Some countries (e.g., USA) believe that land-use changes are helpful towards increasing carbon sequestration and reducing greenhouse gas emissions; growing trees sequestrates and conserves carbon within the organism, which contributes to the reduction of greenhouse gases, and hence are supportive towards LUCF: Some countries on the world (e.g., some European countries), however, oppose the idea of giving carbon credits to the LUCF activities. The opposition argues that the carbon sequestrated through LUCF projects may be released again into the atmosphere later on when the timber is being harvested/logged, and the reduction of greenhouse gas emissions is merely a short term effect. On the contrary, greenhouse gas emissions reduced through energy-saving enhancements are permanent. In other words, the contract period plays an

[1] Woerdman (2001) suggested that although emission trading reduces the costs of reducing greenhouse gas emissions, the trading costs may compromise the cost effectiveness of the emission trading policy. In theory, however, transaction costs arising from joint implementation and Clean Development Mechanism are both higher than the emission trading policy (International Emission Trading).

important factor in carbon trading arrangements because the effects of carbon sequestration are short-lived. Past researches (e.g., see Smith et al., 2000) pointed out that short term afforestation policies merely postponed carbon emission, while energy-saving policies are long term plans that may permanently reduce carbon emission. Thus, short term afforestation policies are perceived by some countries as preliminary policies and methods. However, as the Kyoto Protocol became effective in 2005, the reduction of emissions using LUCF methods became legally enforced as well; since it is widely perceived throughout the world that afforestation and LUCF schemes are still beneficial towards other policies relating to the reduction of greenhouse gases: (1) When trees are cut, not all carbon is released into the atmosphere. Depending on the use of timber, the carbon may be stored permanently; (2) overall, delaying the release of carbon still contributes to the reduction of greenhouse gases to some degree; (3) while trees sequestrate carbon, they create some buffer period so that energy-intensive industries have sufficient time to investigate and develop technologies or production processes that reduce greenhouse gas emission (Lecocq and Chomitz, 2001; Cacho et al., 2003).

Many countries are focusing on carbon sequestration through forests as a mean to reduce emission, and the conversion of agricultural land into plantation to sequestrate carbon has become a widely adopted method of controlling greenhouse gas emission by countries all over the world. The development of emission trading policies also helps lower the government's financial burden while improving market efficiency, and thus has become an important tool as well as a growing trend to every country's domestic policies (Thomassin, 2003). According to the statistics provided by the OECD (1997), a total of US$11 billion was spent by 14 countries across Europe between 1993 and 1997 to help convert 20 million hectares of agricultural land into afforestation. In the USA, the Conservation Reserve Program (CRP), which was introduced by the government to encourage the afforestation of agricultural lands, costs approximately US$1.5 billion per year to convert 12 million hectares of agricultural land into plantation (Ferraro and Simpson, 2002). Although carbon sequestration policies exist, only a few farmers are willing to permanently convert agricultural land into plantation, and these converted agricultural lands shall provide permanent carbon sequestration. Most farmers are willing to utilize their lands for carbon sequestration only during the contract period, since income from afforestation is relatively lower. When contracts expire, landowners are entitled to cut all trees on the lands; thereby releasing the sequestrated carbon back into the atmosphere and reducing the overall environmental benefits to society (Lee and McCarl, 2003).

Some countries (e.g., Taiwan) has drafted greenhouse gas reduction laws; the contents not only included administrative management policies on CO_2 reduction that provide a legislative foundation for greenhouse gas reduction, but also a plan to establish industrial CO_2 inspection and registration policies, and a coordination mechanism for cross-industry CO_2

reduction. The carbon trading policies are also under development. Due to the unattractive pricing of forestry products, foresters are still reluctant towards afforestation. If an emission trading mechanism can be properly developed, not only are we able to solve the difficulties faced by forestry industry by providing the economic incentives, we may also improve our natural environment and preserve the diversity of our ecological system; thereby achieving a three-win situation among the economy, the society, and the ecology. If emission trading policies are to be implemented, we must first consider how deals are determined between the forestry and non-forestry participants.

Generally speaking, a deal price is equilibrium between the lowest price that sellers are willing to sell and the highest price that buyers are willing to buy. There are many relevant researches (Chomitz1 and Lecocq, 2003; Cacho et al., 2003) and theories (Olshewski et al., 2005) available, but documented discussions on such topics are scarce in Taiwan. Moura-Costa and Wilson (2000) and Cacho et al. (2003) have proposed four methods of emission trading. In this study, we develop theoretical supply and demand models based on these four methods to identify the first order condition to determine the optimal trading price with endogenous and exogenous carbon prices, with the hope of providing references to the establishment of trading mechanisms during the post-Kyoto Protocol era. This study is divided into three sections: Section I - Introduction, Section II - The Carbon Contract Model, Section III - Conditions of Equilibrium in Carbon Contract, and Section IV - Conclusion.

2. The Carbon Contract Model

2.1 The Demand for Carbon Contract

On the demand side, we have adopted the model which was developed by Olschewski et al. (2005). For a manufacturer or company who needs to reduce its carbon emission, he/she may choose to reduce the amount of actual emission, or purchase carbon sequestration credits from the carbon trading market. In other words, the buyer may choose to: (1) to investigate and development new technology or purchase advanced equipment that produces less gages emissions. The net present value of its cost in an infinite horizon is denoted as p_∞: (2) to deal a contract with landowners to purchase carbon credit from forests for a contract period of *T*, and to seek to reduce actual emission when the contract expires at time *T*. The net present value of its costs in an infinite horizon is $p_b + p_\infty\, e^{-r \cdot T}$. If the buyer is willing to deal with the seller, the following equation must be satisfied:

$$p_\infty \geq p_b + p_\infty\, e^{-r \cdot T} \tag{1}$$

where *T* denotes the contract period of an emission trading arrangement, p_b is the net present value of emission trading contract in an infinite horizon (\$/ton), r is the buyer’s discount rate, and p_∞ is the net present value of buyer’s cost to reduce actual emission (\$/ton). Equation

(1) represents that the buyer's cost to reduce actual emission must be greater or equal to the cost of purchasing an emission trading contract plus the net present value cost of reducing actual emission after contract expiry; only under this circumstance will the buyer have the incentive to trade.

After rearranging, Equation (1) becomes:

$$p_b \leq p_\infty - p_\infty\, e^{-r \cdot T} = p_\infty (1 - e^{-r \cdot T}) \tag{2}$$

Hence the maximum price at which the buyer is willing to enter into an emission trading arrangement may be restated as:

$$p_b^{\max} = p_\infty (1 - e^{-r \cdot T}) \tag{3}$$

2.2 The Supply for Carbon Contract

The supplier in an emission trading arrangement is a forester who has signed a contract with the buyer; this generally means planting trees on barren forest lands[2], or converting agricultural lands into plantations[3]. This study models the conversion of agricultural lands into plantations and analyzes using the Net Present Value (NPV) maximization approach. In the absence of an emission trading mechanism, a landowner is willing to convert agricultural land into plantation only if the net present value of afforestation (NPV_F) is greater than the net present value of agriculture (NPV_A), as described by the following equation:

$$NPV_F \geq NPV_A \tag{4}$$

If a trading mechanism exists, an owner earns carbon income during the afforestation period on top of the income from timber, if he/she chooses to convert agricultural land into plantation. Thus if the net present value of harvesting timber plus the net present value of carbon sequestration income is greater than the net present value of agricultural income, the landowner will favor afforestation:

$$NPV_F = R(T) + B^T \geq NPV_A \tag{5}$$

where $R(T)$ is the net present value of harvesting the reforested timber at time T by the landowner ($/hectare), and B^T is the net present value of the landowner's carbon sequestration income ($/hectare) over the course of afforestation. Thus, Equation (5) represents that a landowner who is willing to reforest if the net present value of timber harvest plus the net present value of carbon sequestration income is greater than or equal to agricultural uses.

The term B^T in Equation (5) involves the timing of payments, and thus determines the

[2] Such as the nationwide reforestation program implemented in Taiwan back in 1997, which was terminated at the end of 2004.
[3] Such as the landscape afforestation policy of plain area implemented in Taiwan back in 2002, which was terminated at the end of 2007.

duration of seller's afforestation. In this study we establish four scenarios based on past researches to describe the different timeframes in which sellers collect their pay, including the *Ideal Scenario* that is best suited for our theoretical and economic foundation but not feasible in practice, *Tonne-Year Scenario* and *Ex-Ante Full Crediting Scenario*, which is best suited for implementing for the government due to annual pay, and *Ex-Post Full Crediting Scenario*, which is easy for policy implementation but may decrease the incentives of poor foresters' participation; we further derived the optimal first order conditions as we set carbon prices as exogenous and endogenous variables.

2.2.1 Ideal Scenario

In theory, foresters should collect their carbon sequestration income at the same time as carbon sequestration occurs; similarly, as trees are logged, part of the sequestrated carbon is released back into the atmosphere and thus the foresters should bare the expenses of partial emission. This payment method is the most ideal but not feasible in practice (Cacho et al., 2003).

Let us consider a landowner who converts agricultural land into plantation to participate in emission trading arrangements with a contract period of T periods. The net present value to the landowner for the next T periods is presented as the following equation:

$$\pi(T) = v(T)\cdot p_v \cdot e^{-rT} - c_E + \int_0^T \dot{b}(t)\cdot \upsilon \cdot p_b \cdot e^{-rT} dt - b(T)\cdot \upsilon \cdot p_b \cdot e^{-rT} \tag{6}$$

where $\pi(T)$ denotes the landowner's net present value for participating in the T period reforesting contract, $v(T)$ is the timber volume at time T (cubic meter/hectare), p_v is the unit price of timber at time T ($/cubic meter), r is the discount rate, c_E is the present value of afforestation ($/hectare), $b(t)$ is the cumulative volume of carbon sequestration (ton/hectare) at time t, υ is the conversion coefficient for converting stored carbon into CO_2, and p_b is the unit price of carbon sequestration ($/ton). $v(t)$ and $b(t)$ are both state variables. Equation (6) represented[4] that the net present value to the seller of an emission trading arrangement equals to income from timber harvest at time T, minus the cost of afforestation, plus carbon sequestration income earned during period T, and deduct the expense of releasing carbon after logging. The $\pi(t)$ in Equation (6) is the single rotation period profitability function of the forest, and if the timeframe is extended indefinitely, the landowner's net present value of

[4] Equation (6) implies that the amount of carbon sequestration accumulated during the growth of the forest and the amount of carbon released at the time of logging are transparent information, and can be estimated accurately. However the Ideal Scenario is not feasible in practice for the following three main reasons: first is the extensive cost of accurately measuring the amount of annual carbon sequestration for each specie of tree per unit area; second is the inability of the market to fully monitor the sellers' behaviors and there is no way to ensure that sellers will continually comply with the rotation period to maintain the infinite carbon cycle (as shown in equation (7)). Furthermore the soil conditions and the effectiveness of carbon sequestration tend to change, the longer the land is used; third is the uncertainty regarding how much carbon is released at the time of logging, which largely depends on the use of timber. Equation (6) assumed that all carbon is released into the atmosphere. If we were to calculate the expense of carbon emission after logging for the various uses of timber, the amount of carbon emission per year is difficult and impractical to calculate.

afforestation for infinite rotation periods becomes:

$$NPV_F = \pi(T) + \frac{\pi(T)}{e^{rT}-1} = \left(\frac{1}{1-e^{-rT}}\right)\pi(T) \tag{7}$$

2.2.1.1 p_b is exogenous and T is endogenous

If p_b is determined as exogenous, from the landowner's perspective, we can derive the optimal rotation period T^* by maximizing the net present value in an infinite number of rotation periods, which shall be the optimal contract period to the landowner. Thus under the ideal scenario, the landowner's decision is modeled in the equation below:

$$\underset{T}{Max}\, NPV_F = \pi(T) + \frac{\pi(T)}{e^{rT}-1} = \left(\frac{1}{1-e^{-rT}}\right)\pi(T) = \left(\frac{1}{1-e^{-rT}}\right)\left(v(T)\cdot p_v \cdot e^{-rT} - c_E + \int_0^T \dot{b}(t)\cdot \upsilon \cdot p_b \cdot e^{-rt}dt - b(T)\cdot \upsilon \cdot p_b \cdot e^{-rT}\right) \tag{8}$$

Differentiate T and we shall obtain the first order condition as follows:

$$\dot{v}(T)\cdot p_v \cdot e^{-rT}(1-e^{-rT}) + re^{-rT}\cdot c_E + rb(T)\cdot \upsilon \cdot p_b \cdot e^{-rT} = rv(T)\cdot p_v \cdot e^{-rT} + re^{-rT}\cdot \int_0^T \dot{b}(t)\cdot \upsilon \cdot p_b \cdot e^{-rt}dt \tag{9}$$

2.2.1.2 p_b is endogenous and T is exogenous

If the contract period T has already been determined exogenously (e.g., determined by social planners), T becomes an exogenous variable and we can derive the lowest price of supply p_b at which a landowner is willing to convert agricultural lands into plantation. Substitute Equation (6) into Equation (7), then substitute back into Equation (5) and we have:

$$\left(\frac{1}{1-e^{-rT}}\right)\left\{v(T)\cdot p_v \cdot e^{-rT} - c_E + \int_0^T \dot{b}(t)\cdot \upsilon \cdot p_b \cdot e^{-rt}dt - b(T)\cdot \upsilon \cdot p_b \cdot e^{-rT}\right\} \geq \left(\frac{1}{1-e^{-rT}}\right)NPV_A \tag{10}$$

As Equation (10) shows, the NPV_A in Equation (5) also represented the net present value of agricultural land use for T periods; hence similar to Equation (7), the right-hand term of Equation (8) must, too, be multiplied by the annuity factor $\left(\frac{1}{1-e^{-rT}}\right)$ to derive Equation (10). From Equation (10) we obtained:

$$p_b \geq \left(NPV_A - \left[v(T)\cdot p_v \cdot e^{-rT} - c_E\right]\right) / \left(\int_0^T \dot{b}(t)\cdot \upsilon \cdot e^{-rt}dt - b(T)\cdot \upsilon \cdot e^{-rT}\right) \tag{11}$$

Thus in an emission trading contract, the lowest price acceptable to the landowner is:

$$p_b^{\min} = \left(NPV_A - \left[v(T)\cdot p_v \cdot e^{-rT} - c_E\right]\right) / \left(\int_0^T \dot{b}(t)\cdot \upsilon \cdot e^{-rt}dt - b(T)\cdot \upsilon \cdot e^{-rT}\right) \tag{12}$$

2.2.2 Tonne-Year Scenario

The first scenario incorporated the idea that sellers must pay for the emission carbon at the time of logging, which is not feasible in practice. Since most sellers in an emission trading arrangement are not required to bear the carbon emission expense, Moura-Costa and Wilson (2000) proposed an annuity payment method whereby the market certifies sellers' afforestation progresses on an annual basis. Only certified sellers are entitled to receive carbon sequestration income[5]; see Equation (13):

$$\pi_E(T) = v(T)\cdot p_v \cdot (1+r)^{-T} - c_E + \sum_{t=0}^{T}[\dot{b}(t)\cdot \upsilon \cdot p_b \cdot (1+r)^{-t}] \tag{13}$$

As shown in Equation (13), the discounting method used here is different from the method used in the first scenario; the main difference is that here the market pays on a yearly basis. In Equation (13), T represents the contract period (the duration of a landowner's afforestation), the right-hand term $v(T)\cdot p_v \cdot (1+r)^{-T}$ represents the present value of logging income in the T^{th} year (\$/hectare), c_E is the present value of afforestation costs (\$/hectare) and the third term on right side is the present value of carbon sequestration income. In this scenario, the seller does not need to pay for emitting carbon at the time of logging. π_E (T) in Equation (13) is the profitability function for a single rotation period; if there is an infinite number of rotation periods, the net present value of afforestation to the landowner becomes the following:

$$NPV_F = \pi_E(T) + \frac{\pi_E(T)}{e^{rT}-1} = \left(\frac{1}{1-e^{-rT}}\right)\pi_E(T) \tag{14}$$

2.2.2.1 p_b is exogenous and T is endogenous

If p_b is determined as an exogenous variable, from the landowner's perspective, we can derive the optimal contract period T^* (i.e., the optimal rotation period) by maximizing the net present value in an infinite number of rotation periods. Hence, in the Tonne-Year Scenario, the landowner's decision is modeled in the equation below:

$$\underset{T}{Max} \quad NPV_F = \pi_E(T) + \frac{\pi_E(T)}{e^{rT}-1} = \left(\frac{1}{1-e^{-rT}}\right)\pi_E(T) = \left(\frac{1}{1-e^{-rT}}\right)\left\{v(T)\cdot p_v \cdot (1+r)^{-T} - c_E + \sum_{t=0}^{T}[\dot{b}(t)\cdot \upsilon \cdot p_b \cdot (1+r)^{-t}]\right\} \tag{15}$$

Differentiate T and we shall derive the first order condition as follows:

$$\begin{aligned}&\left(\dot{v}(T)\cdot p_v \cdot(1+r)^{-T} - v(T)\cdot p_v\cdot(1+r)^{-T}\cdot\ln(1+r) + \dot{b}(T)\cdot\upsilon\cdot p_b\cdot(1+r)^{-T}\right)\cdot(1-e^{-rT})\\ &= re^{-rT}\left(v(T)\cdot p_v\cdot(1+r)^{-T} - c_E + \int_0^T \dot{b}(t)\cdot\upsilon\cdot p_b\cdot(1+r)^{-t}dt]\right)\end{aligned} \tag{16}$$

[5] Using this method, the market does not need to impose restrictions to sellers on how many years the lands must remain forested, since the sellers are certified and adjusted on a yearly basis.

2.2.2.2 p_b is endogenous and T is exogenous

If T is determined as an exogenous variable, we can further derive the lowest price at which a landowner is willing to convert agricultural land into plantation in the Tonne-Year Scenario (p_b). Substitute Equation (13) into Equation (14), then substitute back into Equation (5) and we have:

$$\left(\frac{1}{1-e^{-rT}}\right)\left\{v(T)\cdot p_v\cdot(1+r)^{-T}-c_E+\sum_{t=0}^{T}[\dot{b}(t)\cdot\upsilon\cdot p_b\cdot(1+r)^{-t}]\right\}\geq\left(\frac{1}{1-e^{-rT}}\right)NPV_A \quad (17)$$

We can further derive

$$p_b\geq\left(NPV_A-\left[v(T)\cdot p_v\cdot(1+r)^{-T}-c_E\right]\right)/\left(\sum_{t=0}^{T}[\dot{b}(t)\cdot\upsilon\cdot(1+r)^{-t}]\right) \quad (18)$$

Thus, in the Tonne-Year Scenario, the lowest price acceptable to the seller for entering into an emission trading arrangement is:

$$p_b^{\min}=\left(NPV_A-\left[v(T)\cdot p_v\cdot(1+r)^{-T}-c_E\right]\right)/\left(\sum_{t=0}^{T}[\dot{b}(t)\cdot\upsilon\cdot(1+r)^{-t}]\right) \quad (19)$$

2.2.3 Ex-Ante Full Crediting Scenario

Moura-Costa and Wilson (2000) also proposed another payment method, whereby the sellers are awarded carbon credits in full for T periods when afforestation commences, but the sellers must continue with afforestation for (T+T_e) years before logging. In other words, the logging is postponed by T_e years. This serves as the price sellers must pay for receiving carbon sequestration income early; see Equation (20):

$$\pi_A(T+T_e)=v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)}-c_E+b(T)\cdot\upsilon\cdot p_b \quad (20)$$

As shown in Equation (20), the landowner receives T periods of carbon sequestration income totaling $b(T)\cdot\upsilon\cdot p_b$, at the commencement of afforestation, but is not permitted to log until (T+T_e) years later. Income from logging is represented as $v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)}$. Since the investment horizon of forestry is relatively long and the majority of capital expenditure is made during the initial stages of afforestation, this payment method provides early carbon sequestration income that may serve as incentives to landowners for participating in afforestation trading arrangements.[6]

π_A (T+T_e) in Equation (20) is the profitability function for a single rotation period; if there is an infinite number of rotation periods, the net present value of afforestation to the landowner becomes the following:

[6] The prerequisite of this method is the assumption that the costs of monitoring landowners' extension for T_e years are minimal.

$$NPV_F = \pi_A(T+T_e) + \frac{\pi_A(T+T_e)}{e^{r(T+T_e)}-1} = \left(\frac{1}{1-e^{-r(T+T_e)}}\right)\pi_A(T+T_e) \tag{21}$$

2.2.3.1 p_b is exogenous and T is endogenous

If p_b is determined as an exogenous variable, from the landowner's perspective, we can derive the optimal contract period T^* by maximizing the net present value in an infinite number of rotation periods. Hence, in the Ex-Ante Full Crediting Scenario, the landowner's decision is modeled as follows:

$$\begin{aligned}\underset{T}{Max} \quad NPV_F &= \pi_A(T+T_e) + \frac{\pi_A(T+T_e)}{e^{r(T+T_e)}-1} = \left(\frac{1}{1-e^{-r(T+T_e)}}\right)\pi_A(T+T_e) \\ &= \left(\frac{1}{1-e^{-r(T+T_e)}}\right)\left[v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)} - c_E + b(T)\cdot \upsilon \cdot p_b\right]\end{aligned}$$

(22)

Differentiate T and we shall derive the first order condition as follows:

$$\begin{aligned}&\dot{v}(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)} + \dot{b}(T)\cdot\upsilon\cdot p_b\cdot(1+e^{-r(T+T_e)}) + re^{-r(T+T_e)}\cdot\left(c_E - b(T)\cdot\upsilon\cdot p_b\right) \\ &= v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)}\left[(1+e^{-r(T+T_e)})\ln(1+r) + re^{-r(T+T_e)}\right]\end{aligned} \tag{23}$$

2.2.3.2 p_b is endogenous and T is exogenous

If T is determined as an exogenous variable, we can derive the lowest price at which a landowner is willing to convert agricultural land into plantation in the Ex-Ante Full Crediting Scenario (p_b).

Substitute Equation (20) into Equation (21), then substitute back into Equation (5) and we have:

$$\left(\frac{1}{1-e^{-r(T+T_e)}}\right)\left\{v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)} - c_E + b(T)\cdot\upsilon\cdot p_b\right\} \geq \left(\frac{1}{1-e^{-rT}}\right)NPV_A \tag{24}$$

We can further derive

$$p_b \geq \left(\left(\frac{1-e^{-r(T+T_e)}}{1-e^{-rT}}\right)NPV_A - \left[v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)} - c_E\right]\right) / \left(b(T)\cdot\upsilon\right) \tag{25}$$

Thus, in the Ex-Ante Full Crediting Scenario, the lowest price acceptable to the seller for entering into an emission trading arrangement is:

$$p_b^{\min} = \left(\left(\frac{1-e^{-r(T+T_e)}}{1-e^{-rT}}\right)NPV_A - \left[v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)} - c_E\right]\right) / \left(b(T)\cdot\upsilon\right) \tag{26}$$

2.2.4 Ex-Post Full Crediting Scenario

Moura-Costa and Wilson (2000) also proposed another method, whereby the sellers receive carbon sequestration income only upon completion of afforestation, but the landowner can start logging only after (T+T_e) years. In other words, sellers receive (T+T_e) years worth of carbon sequestration income only after commencing afforestation for (T+T_e) years; see Equation (27):

$$\pi_p(T+T_e) = v(T+T_e)\cdot p_v \cdot (1+r)^{-(T+T_e)} - c_E + \sum_{t=0}^{T} \dot{b}(t)\cdot \upsilon \cdot p_b \cdot (1+r)^{-(t+1+T_e)} \tag{27}$$

As shown in Equation (27), the right-hand term $v(T+T_e)\cdot p_v \cdot (1+r)^{-(T+T_e)}$ is the net present value of logging in (T+T_e) years ($/hectare), $\sum_{t=0}^{T} \dot{b}(t)\cdot \upsilon \cdot p_b \cdot (1+r)^{-(t+1+T_e)}$ is the net present value of carbon sequestration income to the landowner in year (T+T_e). The disadvantage of this payment method is that carbon sequestration income occurs at a later time and discourages landowners from entering into an emission trading arrangement.[7] π_p (T+T_e) in Equation (27) is the profitability function for a single rotation period; if there is an infinite number of rotation periods, the net present value to the landowner becomes:

$$NPV_F = \pi_p(T+T_e) + \frac{\pi_p(T+T_e)}{e^{r(T+T_e)}-1} = \left(\frac{1}{1-e^{-r(T+T_e)}}\right)\pi_p(T+T_e) \tag{28}$$

2.2.4.1 p_b is exogenous and T is endogenous

If p_b is determined as exogenous, we can derive the optimal contract period T^* by maximizing the net present value in an infinite number of rotation periods. Hence, in the Ex-Post Full Crediting Scenario, the landowner's decision is modeled in the equation below:

$$\begin{aligned}\underset{T}{\text{Max}} \quad NPV_F &= \pi_p(T+T_e) + \frac{\pi_p(T+T_e)}{e^{r(T+T_e)}-1} = \left(\frac{1}{1-e^{-r(T+T_e)}}\right)\pi_p(T+T_e) \\ &= \left(\frac{1}{1-e^{-r(T+T_e)}}\right)\left(v(T+T_e)\cdot p_v \cdot (1+r)^{-(T+T_e)} - c_E + \sum_{t=0}^{T} \dot{b}(t)\cdot \upsilon \cdot p_b \cdot (1+r)^{-(t+1+T_e)}\right)\end{aligned} \tag{29}$$

Differentiate T and we shall derive the first order condition as follows:

$$\begin{aligned}&\left(\dot{v}(T+T_e)\cdot p_v \cdot (1+r)^{-(T+T_e)} - v(T+T_e)\cdot p_v \cdot (1+r)^{-(T+T_e)}\ln(1+r) + \dot{b}(T)\cdot \upsilon \cdot p_b \cdot (1+r)^{-(T+1+T_e)}\right)(1-e^{-r(T+T_e)}) \\ &= re^{-r(T+T_e)}\left(v(T+T_e)\cdot p_v \cdot (1+r)^{-(T+T_e)} - c_E + \int_0^T \dot{b}(t)\cdot \upsilon \cdot p_b \cdot (1+r)^{-(t+1+T_e)}dt\right)\end{aligned} \tag{30}$$

2.2.4.2 p_b is endogenous and T is exogenous

If T is determined as an exogenous variable, we can further derive the lowest price at

[7] There are two advantages to this method. First, the market does not need to monitor the landowners because they receive carbon sequestration income only upon completion of afforestation; second, the landowners receive (T+T_e) years of carbon sequestration income upon completion of afforestation, while in the third scenario described above the landowners only receive T years worth of carbon sequestration income. However, cash inflows to landowners occur only at the final stage of afforestation, and thus reduce landowners' willingness to participate in afforestation trading arrangements.

which a landowner is willing to convert agricultural land into plantation in the Ex-Post Full Crediting Scenario (p_b).Substitute Equation (27) into Equation (28), then substitute back into Equation (5) and we have:

$$\left(\frac{1}{1-e^{-r(T+T_e)}}\right)\left\{v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)}-c_E+\sum_{t=0}^{T}\dot{b}(t)\cdot\upsilon\cdot p_b\cdot(1+r)^{-(t+1+T_e)}\right\}\geq\left(\frac{1}{1-e^{-rT}}\right)NPV_A \quad (31)$$

We can further derive

$$p_b\geq\left(\left(\frac{1-e^{-r(T+T_e)}}{1-e^{-rT}}\right)NPV_A-\left[v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)}-c_E\right]\right)/\left(\sum_{t=0}^{T}\dot{b}(t)\cdot\upsilon\cdot(1+r)^{-(t+1+T_e)}\right) \quad (32)$$

Thus, in the Ex-Post Full Crediting Scenario, the lowest price acceptable to the seller for entering into an emission trading arrangement is:

$$p_b^{\min}=\left(\left(\frac{1-e^{-r(T+T_e)}}{1-e^{-rT}}\right)NPV_A-\left[v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)}-c_E\right]\right)/\left(\sum_{t=0}^{T}\dot{b}(t)\cdot\upsilon\cdot(1+r)^{-(t+1+T_e)}\right) \quad (33)$$

From the four scenarios above, we learn that the first is theoretically the ideal scenario, but with low feasibility in practice; the second, third, and fourth scenario are more practical, but satisfy the basic concepts of economic theories to a lesser degree.

3. Conditions of Equilibrium in Carbon Contract

When T is determined as an exogenous variable and p_b is determined as an endogenous variable, we are able to derive the equilibrium price p_b by calculating the sellers' minimum acceptable price from the seller's supply model, and calculating the maximum price buyers are willing to pay using the buyer's demand model described above. In other words, we set Equation (3) equal to Equations (12), (19), (26) and (33) to derive the price equilibrium equation for emission trading.

3.1 Ideal Scenario

By setting Equation (3) equal to Equation (12) in the Ideal Scenario, we have:

$$p_\infty(1-e^{-r\cdot T})=\left(NPV_A-\left[v(T)\cdot p_v\cdot e^{-rT}-c_E\right]\right)/\left(\int_0^T\dot{b}(t)\cdot\upsilon\cdot e^{-rt}dt-b(T)\cdot\upsilon\cdot e^{-rT}\right) \quad (34)$$

The equilibrium price that attracts both buyers and sellers simultaneously in the Ideal Scenario is:

$$p^*=\left(NPV_A-\left[v(T)\cdot p_v\cdot e^{-rT}-c_E\right]\right)/\left(\left(\int_0^T\dot{b}(t)\cdot\upsilon\cdot e^{-rt}dt-b(T)\cdot\upsilon\cdot e^{-rT}\right)\left(1-e^{-r\cdot T}\right)\right) \quad (35)$$

3.2 Tonne-Year Scenario

In the Tonne-Year Scenario, since buyers pay in annuity, Equation (3) should be amended as:

$$p_b^{\max} = p_\infty\left(1-\frac{1}{(1+r)^T}\right) \tag{36}$$

Setting Equation (36) equal to Equation (19) and we have:

$$p_\infty\left(1-\frac{1}{(1+r)^T}\right)=\left(NPV_A-\left[v(T)\cdot p_v\cdot(1+r)^{-T}-c_E\right]\right)/\left(\sum_{t=0}^{T}[\dot{b}(t)\cdot\upsilon\cdot(1+r)^{-t}]\right) \tag{37}$$

The equilibrium price that attracts both buyers and sellers simultaneously in the Tonne-Year Scenario is:

$$p_E^*=\left(NPV_A-\left[v(T)\cdot p_v\cdot(1+r)^{-T}-c_E\right]\right)/\left(\left(\sum_{t=0}^{T}[\dot{b}(t)\cdot\upsilon\cdot(1+r)^{-t}]\right)\left[1-(1+r)^{-T}\right]\right) \tag{38}$$

3.3 Ex-Ante Full Crediting Scenario

In the Ex-Ante Full Crediting Scenario, the price paid by buyers only covered T periods of carbon emission (i.e., buyers did not pay for the T_e period carbon sequestration that occurs after T periods), thus Equation (3) should be amended as:

$$p_b^{\max} = p_\infty\left(1-\frac{1}{(1+r)^T}\right) \tag{39}$$

Setting Equation (39) equal to Equation (26) and we have:

$$p_\infty\left(1-\frac{1}{(1+r)^T}\right)=\left(\left(\frac{1-e^{-r(T+T_e)}}{1-e^{-rT}}\right)NPV_A-\left[v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)}-c_E\right]\right)/\left(b(T)\cdot\upsilon\right) \tag{40}$$

The equilibrium price that attracts both buyers and sellers simultaneously in the Ex-Ante Full Crediting Scenario is:

$$p_A^*=\left(\left(\frac{1-e^{-r(T+T_e)}}{1-e^{-rT}}\right)NPV_A-\left[v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)}-c_E\right]\right)/\left(b(T)\cdot\upsilon\cdot\left[1-(1+r)^{-T}\right]\right) \tag{41}$$

3.4 Ex-Post Full Crediting Scenario

In the Ex-Post Full Crediting Scenario, the buyer's payment for carbon sequestration covers $T+T_e$ periods of carbon emission, and thus Equation (3) should be amended as:

$$p_b^{\max} = p_\infty\left(1-\frac{1}{(1+r)^{T+T_e}}\right) \tag{42}$$

Setting Equation (42) equal to Equation (33) and we have:

$$p_\infty\left(1-\frac{1}{(1+r)^{T+T_e}}\right)=\left(\left(\frac{1-e^{-r(T+T_e)}}{1-e^{-rT}}\right)NPV_A-\left[v(T+T_e)\cdot p_v\cdot(1+r)^{-(T+T_e)}-c_E\right]\right)/\left(\sum_{t=0}^{T}\dot{b}(t)\cdot\upsilon\cdot(1+r)^{-(t+1+T_e)}\right) \tag{43}$$

The equilibrium price that attracts both buyers and sellers simultaneously in the Ex-Post Full Crediting Scenario is:

$$p_p^* = \left(\left(\frac{1-e^{-r(T+T_e)}}{1-e^{-rT}} \right) NPV_A - \left[v(T+T_e) \cdot p_v \cdot (1+r)^{-(T+T_e)} - c_E \right] \right) / \left(\left(\sum_{t=0}^{T} \dot{b}(t) \cdot \upsilon \cdot (1+r)^{-(t+1+T_e)} \right) \left[1-(1+r)^{-(T+T_e)} \right] \right) \tag{44}$$

4. Conclusion

In this study, we first established a theoretical economic model of supply and demand for four scenarios for carbon trading mechanism, which were proposed during the past researches conducted by Moura-Costa and Wilson (2000), and Cacho et al. (2002), while Olschewski et al. (2005) established a supply and demand trading model under the Clean Development Mechanism. In this study we have modelled our trading methods. In terms of the contributions of this study, we modelled four carbon emission trading scenarios, including the Ideal Scenario, the Tonne-Year Scenario, the Ex-Ante Full Crediting Scenario, and the Ex-Post Full Crediting Scenario for the determination of optimal carbon contract, and derived the optimal pricing conditions to decide the optimal trading price and trading duration of carbon contract with endogenous and exogenous carbon prices. Furthermore we have integrated the theories of supply and demand and solved the conditional equation for the equilibrium price. Hopefully our theoretical analysis can be provided as reference for future studies and help the implementation of the carbon policies or afforestation programs.

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