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Planning the Optimal Afforestation Acreage under Carbon Target: A Case of Taiwan

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ABSTRACT**:** This study mainly analyzes the formulation of afforestation projects and estimates the carbon sequestration potential of afforestation programs in Taiwan from 1990 to 2020. A theoretical model in this paper was developed to determine the optimal afforestation acreage over the period (2008-2020) to achieve the goal of the Kyoto target. By using seven kinds of trees as an example, a simulation model was developed and conducted to find the optimal solution for the afforestation acreage structure. The empirical results revealed that the induction of afforestation acreage 37,494.84 ha per year in the 2008-2020 periods can reach the 5% Kyoto target.

Keywords: Afforestation, Carbon Sequestration, Forest Planning.

INTRODUCTION

The impact of the greenhouse effect on the Earth has become one of the most extensively-researched topics among scientists and environmentalists. When the concentration of greenhouse gases increases continuously, the temperature of the Earth's surfaces will rise and cause abnormal climate changes. Categories of greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), chlorofluorocarbon (CFC), etc, and among them, carbon dioxide is the major composition. Due to the magnitude of its impact towards the greenhouse effect, the problems caused by the emission of carbon dioxide are drawing considerable attention all over the world.

To prevent climate changes, the United Nations passed a United Nations Framework Convention on Climate Change (UNFCCC) in 1992, which was the first worldwide agreement on the control over greenhouse gas (anthropogenic greenhouse gas) emissions. In December 1997, the parties in this agreement passed the Kyoto Protocol during their Third Conference of the Parties to UNFCCC held in Kyoto, Japan. The Kyoto Protocol is the first set of legally-binding and enforced rules agreed among the world in response to the greenhouse effect. It outlined the responsibilities of reducing the greenhouse gas emissions for industrialized countries (UNFCCC, 2005; Environmental Protection Administration, Executive Yuan, 2005).

One prerequisite for the Kyoto Protocol to take effect is that it must be approved by least 55 countries whose carbon dioxide emission in aggregate represents more than 55% of the global greenhouse gas emission in 1990. On 29 July 2004, following the final approval of The Kyoto Protocol by the Russian Congress, this international environmental agreement officially became effective on 16 February 2005. Although Taiwan is not one of the contract parties, it ranked 22th in carbon dioxide emission among the world; the pressure from the contract parties is inevitable and thus the Taiwanese Government must act in advance (Lin, 2005a, 2005b, 2006a, 2006b, 2007, 2008).

There are two common methods of suppressing carbon dioxide emissions among the world. The first is

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through the establishment of regulatory standards, such as the establishment of energy efficiency standards and emission standards that drives the development of energy-saving, fuel conversion and carbon fixation technologies etc; this is the Command and Control approach. The second method involves the use of economic instruments such as the levying of carbon tax, the licensing of emission trading permits, the introduction of afforestation rewards and subsidies, and other economic incentives. Carbon dioxide emissions can be reduced through aggressive carbon tax levies that force tax payers to switch towards low-carbon energy sources; however this drastic measure encounters heavier resistance during execution. There is also a more subtle approach: by rewarding afforestation, we can utilize the natural ecological cycle to achieve reductions in carbon emission (Chen, 1997). Many researchers have concluded that afforestation possesses more carbon sequestration potential than other plants (Li et al, 2000; Wang, 2002; Li et al, 2004).

The Kyoto Protocol outlined the emission controls to 6 greenhouse gases; the base year for CO_2, CH_4, and N_2O controls was 1990 while the base year for HFCs, PFCs, and SF_6 controls was 1995. The Kyoto Protocol also prescribed greenhouse gas reduction targets for 39 countries that entered into this agreement: between the years 2008 and 2012, the volume of greenhouse gases emitted as a result of human activities (converted into a CO_2-equivalent volume) must be reduced to less than 94.8% of 1990s level. One condition worth noting is that forests planted after 1990 can provide CO_2 sequestration credits for the country. The Kyoto Protocol encourages all countries to adopt the ARD approach (Afforestation, Reforestation, and Deforestation) because the costs of reducing emissions are lower than energy-based emission reduction methods; ARD shall no doubt become the interim solution to emission reduction for all countries. Although Taiwan is not one of the contract parties, it still needs to respond to greenhouse gas reductions as early as possible and strive to achieve the greenhouse gas emission reduction and sequestration targets (Sedjo, 1989; Chin, 1992; Dixon et al., 1993; Adams et al, 1993; Pedro et al., 1994; Maclaren, 1996; Wang, 1996; Yang, 1997; Yang, 1998; Lin et al, 1999; Li et al, 2000; Wang, 2002; Hsieh et al, 2003; Li et al, 2004; Lin, 2004, 2005a, and 2006a; Lin, 2003, 2004, 2005b, and 2006b).

What the forestry sector may contribute to this achievement is increasing the carbon sequestration, i.e., maximizing the carbon sequestration under the limited land resources available and suitable for afforestation. This involves either increasing the volume of forest growth stock per unit area within a fixed afforestation acreage, or widening the afforestation acreage under a fixed volume of forest growing stock per unit area. Either approach increases the total carbon sequestration. Since the volume of forest growing stock per unit area is limited, the widening of afforestation acreage is commonly perceived as a more feasible approach. So far there have been no previous researches on the empirical analysis of greenhouse gas reductions through afforestation in Taiwan which have achieved the targets set by the Kyoto Protocol.

In this paper, we develop a general model that incorporates afforestation as the greenhouse gas reduction method, set to achieve a certain greenhouse gas sequestration target within a specified timeframe, such as the standards outlined in the Kyoto Protocol, with minimal government spending. This model shall provide references to how afforestation acreages should be provided between the years 2008 and 2020. An adjustment coefficient: the proportion of the total sequestration target contributed by the forestry sector is introduced into the model to represent simultaneous contributions from other sectors toward a greenhouse gas reduction strategy.

This rest of this paper is organized as follows: Section II is the Programming Model of Afforestation Acreage under Kyoto Protocol Target; Section III is the Simulation Results, Section IV contains conclusions.

MATERIALS AND METHODS

How should we provide for the afforestation acreage in order to achieve the level of carbon emission set forth by the Kyoto Protocol? In this paper, we have established a general model which incorporates afforestation as the greenhouse gas reduction method, set to achieve a certain greenhouse gas sequestration target within a specified timeframe, while minimizing government spending. An adjustment coefficient: the proportion of the total sequestration target contributed by the forestry sector is introduced into the model to represent simultaneous contributions from other sectors toward the greenhouse gas reduction strategy. In other words, this model shall help the government determine the amount of afforestation acreage on a yearly basis, which aligns with the collective carbon emission volume control at minimal government spending. In this paper, we assume that the government's spending on afforestation is in the form of afforestation rewards. The optimization principle implies that the optimal state is achieved when marginal cost equals marginal benefit; therefore if we assume the amount of afforestation rewards granted by the government each term as the marginal cost per unit of carbon sequestration potential, we shall develop the following model:

$$\textit{Minimize} \quad \sum_{t=1}^{Y} \gamma(t) e^{-rt}$$

$$\gamma(t) = \sum_{q=U_0}^{U_t} c(q), U_0 = 0$$

$$U_t = \sum_{k=1}^{t} \sum_{j=1}^{m} S_{k,j} X_{t-k+1,j} \text{ for } t > 0$$

subject to

$$\sum_{t=1}^{Y} \sum_{j=1}^{m} S_{t,j} X_{Y-t+1,j} \geq \omega[C(Y) - (1-\beta)C_0]$$

$$\gamma(t) \leq B(t),\ t = 1,2,\ldots,Y,\ j = 1,2,\ldots,m \quad (1)$$

$\gamma(t)$: government's total spending (dollars) in year t

U_t: carbon sequestration potential (tons) in year t

$c(q)$: marginal cost (\$/tons) per unit of carbon sequestration potential at q tons

$S_{t,j}$: carbon sequestration potential (tons/ ha) of tree species j at age t

$X_{t,j}$: plantation acreage (ha) of tree species j at age t

$B(t)$: cap on afforestation budget (dollars) in year t

$C(Y)$: carbon emission (tons) in the target year

C_0: carbon emission (tons) in the base year

ω: proportion of carbon dioxide reduced by the forestry sector

β: carbon emission reduction rate in the base year

r: discount rate

Y: target year

In model (1), the objective function is the minimization of the government's total spending, i.e. minimizing the net present value of afforestation spending within timeframe [1, Y]. The afforestation spending can be defined as the afforestation rewards granted by the government, and in the optimal state, the afforestation reward per unit equals the marginal cost of afforestation. The higher the target carbon sequestration, the larger the land that must be provided for afforestation, and marginal cost increases under limited land resources. Hence, if we assume the afforestation reward per unit as a function of target carbon sequestration, it implies that the higher the target carbon sequestration, the higher the marginal cost of sequestrating the final unit of carbon. the constraint is that the total carbon sequestration potential of trees of different ages must satisfy at least the carbon emission reduction target in target year Y. In other words, carbon sequestration potential provided by afforestation acreage must cover, not only the net increase in carbon emission between the base year and the target year, but also the reduction rate under the specified target. The constraint also restricts that annual afforestation rewards granted by the government must not exceed the cap on the afforestation budget. Since alternative carbon dioxide reduction strategies are available, such as the rebalancing of industry focus to reduce carbon emission etc, we further assume the proportion of carbon dioxide reduced through afforestation as ω (representing the contribution of the forestry sector towards emission reduction). This ω has a value between [0, 1], and (1-ω) represents the contribution of non-forestry sectors towards emission reduction. Additionally, these data of five tree species including *Cinnamomum camphora*, *Calocedrus formosana*, *Acacia catechu*, *Cryptomeria japonica*, *Cunninghamia lanceolata*, and *Fraxinus formosana* are used for examples to analyze the optimal afforestation acreage under carbon target.

RESULTS AND DISCUSSION

Variable estimates

(A) Marginal cost of carbon sequestration ($c(q)$)

Historical attempts at calculating the marginal cost of afforestation in Taiwan include Chen (1997), who conducted estimation and simulation according to an agricultural model. When 5 million tons of carbon dioxide is being sequestrated through afforestation, the marginal cost of sequestrating the final unit was only 0.14; but as the sequestration target increases, the marginal cost rises. When 21 million tons are being sequestrated, the marginal cost of sequestrating the final unit reaches $1,191. In addition, Liu (1997) estimated the cost of afforestation at $102,000 (Liu, 1997)[1] per ha while Liu (2004) estimated an optimal afforestation reward of $269,299.94 for 20 years of plantation. For the convenience of calculation and analysis, the simulation analysis in this paper adopts the settings of Liu (1997).

(B) The carbon sequestration potential function ($S_{t,j}$)

The government's previous afforestation reward policies subsidize the plantation of more than 40 tree species[2]; however researches on the pattern of carbon sequestration potential were not available for all tree species at all ages. Under limited data, the study by Lin et al. (2002) was adopted into this research; we estimated the growth potential of every tree species based on the growth model and substituted the estimation and the conversion coefficient into the carbon dioxide sequestration capacity evaluation model. They are considered as representative species and shall be used in our simulation analysis in this paper. Under the assumption that the marginal cost of every species is equal, the annual carbon sequestration potential equals the annual sequestration potential of the specie with the largest capacity. Assumption 1 is valid as described below.

Assumption 1: Assume that the marginal costs of all species are equal, i.e. $c_i = c_j$ for all i, j at any time t; let $j(t)$ be the specie with the largest carbon sequestration potential in year t and $S_{t,j}(t) \geq S_{t,i}$ for all species i. the optimal solution for equation (1) above is $i \neq j(t)$, $X_{t,i} = 0$ for all species and time t.

(C) The carbon dioxide emission baseline forecast model $C(t)$

In this paper, we adopted the study conducted by Hsu (2005) and forecasted Taiwan's carbon dioxide emission base line based on Taiwan's population, technologies, macroeconomics, industry structure, economic growth rate and other variables. We have also forecasted the nation's carbon dioxide emission base lines under different GDP growth scenarios. From their research results we have discovered that the TAIGEM-D model had simulated historical GDP growth rates that approximate closely to the actual figures announced by the Directorate General of Budget, Accounting, and Statistics. According to the results forecasted by the model, our nation's total CO_2 emission is 402 million tons in year 2020 (Wang and Hsu,1997; Huang et al., 1998; Hsu, 2005; Hsu and Chiang,1997; Liang, 1998; Yang et al.,1998; Huang et al, 1999, 2001; Hsu, 2005). We shall conduct evaluation and analysis based on this estimate.

(D) Other parameters

The Kyoto Protocol specified that forests planted after 1990 may contribute to the reduction of carbon dioxide of their respective countries. The most significant afforestation schemes in Taiwan after 1990 were the Afforestation on Agriculture Land Program, the Reforestation Policy, and the Plain Landscape Afforestation Program, while the Green Mass Program and the Green Afforestation Policy are currently under development. The Green Afforestation Policy shall be implemented in 2009. The Afforestation on Agriculture Land Program has been merged into the Reforestation Policy since 1996; new forests planted between 1990 and 2004 mainly grew on the acreage provided by the Reforestation Policy. The Reforestation Policy authorized a total acreage of 37,780.94 ha, including 597.6 ha in 1991, 1,197.28 ha in 1992, 1,460.39 ha in 1993, 1, 430.34 ha in 1994, 1,985.20 ha in 1995, 2,423.59 ha in 1996, 3,089.04 ha in 1997, 4,488.81 ha in 1998, 5,208.25 ha in 1999, 3,959.64 ha in 2000, 3,555.20 ha in 2001, 3,869.22 ha in 2002, 1,825.55 ha in 2003, and 2,690.83 ha in 2004. The Plain Landscape Afforestation Program authorized

[1] The afforestation costs are thus estimated at NT$102,000 per ha for 20 years (Liu, 1997).

[2] Please refer to the Forestry Bureau, Council of Agriculture, Executive Yuan (2002), for detailed tree species.

a total acreage of 8,919.18 ha between 2002 and 2007, including 1,589 ha in 2002, 4,072.17 ha in 2003, 1,324.83 ha in 2004, 1,022.10 ha in 2005, 460.92 ha in 2006, and 450.05 ha in 2007. Marginal carbon sequestration potentials provided by these new plantations each year should be included in our carbon dioxide reduction progress (Chen, 2007; Executive Yuan, 2008).

In this paper, we assumed that the planning for new plantations begins in 2008; we shall designate 2008 as The Year of Governance and set our 2020 target carbon sequestration potential of new plantations to a certain proportion. According to the Kyoto Protocol, the carbon sequestration capacity produced by new plantations created during 1990-2007 may contribute towards the carbon dioxide reduction progress. By 2008-2012, parties to this agreement must also reduce greenhouse gases emitted as a result of human activities by 5.2% compared to their respective levels in 1990. However it is extremely challenging for Taiwan to set its target year of greenhouse gas reduction in 2012, since Taiwan is currently making rapid economic developments and thus has growing carbon emissions. Therefore, this paper adopted the conclusion of the 1998 National Energy Conference and set the target year as 2020, while the reduction percentage still followed the original guidelines set forth in the Kyoto Protocol, being 5.2% lower than the emission level in the base year. Based on the settings above, we adjusted theoretical model (1) into empirical model (2) to facilitate simulations.

Minimize $$\sum_{t=1}^{Y}\sum_{j=1}^{m} e^{-rt} c_j X_{t,j}$$

Subject to

$$\sum_{t=1}^{Y}\sum_{j=1}^{m} X_{Y-t+1,j} S_{t,j} \ge \omega[C(Y)-(1-\beta)C_0-V]$$
$$X_t = X_s \text{ , } \forall t,s \in \{1,2...Y\} \qquad (2)$$

As described in equation (2) above, $X_{t,j}$ represents the acreage of new plantation for tree species j in year t; c_j represents the carbon sequestration capacity of tree species j; r is the discount rate; Y is the target year. ω represents the amount of carbon sequestration capacity produced by new plantations in proportion to the total emission reduction; $C(Y)$ is the carbon emission in year Y; C_0 is the carbon emission in the base year (year 1990); β is the reduction percentage; V is the total marginal carbon sequestration capacity in year Y produced by new plantations created between 1990 and 2007. Furthermore, if landscape factors are taken into account, we can fix the annual afforestation acreage and add in the following constraint: $X_t = X_s$, $\forall t,s \in \{1,2...Y\}$.

Simulation results of the new plantation acreage model

Based on the above assumptions, we reconstructed model (2) and derived the following solution: if the goal of the social planners is to achieve a carbon dioxide emission level that is 5.2% less than the 1990 emission level by year 2020, then we seek to minimize the net present value of afforestation reward expenses (the marginal cost of carbon sequestration), and the solution for the allocation of new plantation acreage shall converge towards the 11th year totaling 7,995,590.24 ha.

If the allocation of plantation acreage is assumed to be spread evenly from 2008 to 2020, and taking into account landscape factors and the government's budgetary constraints, new plantation acreage allocated per year between 2008 and 2020 amounts to 749,897.39 ha. In other words, under the assumptions of this research, we can achieve the emission reduction framework outlined in the Kyoto Protocol by year 2020 without adjusting our industry structure which jeopardizes our economic growth, if we can either allocate new plantation acreage totaling 7,995,590.24 ha in year 2015, or 749,897.39 ha per year from 2008 to 2020. However, since land resources are extremely scarce in Taiwan, it is not practical for the forestry sector to handle the full reduction target outlined in the Kyoto Protocol; hence we have further assumed that the reduction of carbon emission is jointly borne by the forestry and non-forestry sectors. The proportional contribution made by the forestry sector is denoted as ω (ω with values less than 1). From assumption 2 below, we know that there is a constant proportion between the adjustment ratio of the forestry sector and the optimal solution.

Assumption 2: If X = $[X_{t,j}]_{Y\times m}$ is the set of optimal solution for (*) when $\omega = 1$, if and only if, ρX is the set of optimal solution for (*) when $\omega = \rho$.

Proof:

Minimize $\sum_{t=1}^{Y}\sum_{j=1}^{m} e^{-rt} c_j X_{t,j}$

subjectto

$$\sum_{t=1}^{Y}\sum_{j=1}^{m} X_{Y-t+1,j} S_{t,j} \geq \omega[C(Y)-(1-\beta)C_0 - V] \quad (3)$$

Since the left hand terms of the objective and the constraint in (3) above were both linear functions of **X**, this assumption is valid. Based on assumption 2 above, we can derive that if the social planners seek to minimize government spending when the forestry sector is contributing 10% towards emission reduction, i.e. ω=0.1, 799,559.02 ha of new plantation acreage is required. If we take landscape factors and the government's budgetary constraints into consideration, then 74,989.74 ha of new plantation must be created each year between 2008 and 2020 in order to achieve the 10% contribution quota demanded from the forestry sector. Similarly if the social planners seek to minimize government spending when ω=0.05, then 399,779.51 ha of new plantation acreage are required. If we take landscape factors and the government's budgetary constraints into consideration, then 37,494.84 ha of new plantation must be created each year between 2008 and 2020 in order to achieve the contribution quota demanded from the forestry sector. Similarly if the social planners seek to minimize government spending when ω=0.01, 79,955.90 ha of new plantation acreage is required. If we take landscape factors and the government's budgetary constraints into consideration, then 7,498.97 ha of new plantation must be created each year between 2008 and 2020 in order to achieve the contribution quota demanded from the forestry sector. We understood from the above that Taiwan is currently experiencing high economic growth and thus produces higher carbon emission. If we were to comply with the Kyoto Protocol guidelines within the short timeframe of 13 years (by year 2020) in Taiwan, it must reduce 275.99 million tons of carbon dioxide emission in total. This is an extremely difficult task to be accomplished by the forestry sector alone; the government must coordinate the efforts of both the forestry and non-forestry sectors while making proper industry adjustments to achieve our carbon emission reduction target.

CONCLUSION

In December 1997, during the Third Conference of the Parties to UNFCCC held in Kyoto, Japan, the legally-binding Kyoto Protocol was passed and came to effect on 16 February 2005. Taiwan must focus on reducing carbon dioxide emissions through afforestation policy; it is one of the more subtle means available that utilizes the nature's ecological cycle without creating significant impacts to the industry or the economy. This paper was aimed to establish an afforestation acreage planning model that is set to achieve a certain greenhouse gas sequestration target within the timeframe guidelines specified in the Kyoto Protocol, using afforestation as a measure for reducing greenhouse gas emissions.

What strategic planners can decide for the forestry sector is the amount and the timing of providing new plantation acreages for afforestation under limited land resources. In this paper, we have modeled the achievement of certain greenhouse gas sequestration targets within a specified time frame, such as the ones set out in the Kyoto Protocol, by minimizing government's spending. An adjustment coefficient was also introduced into the model to represent the amount of contribution made by the forestry sector in proportion to the overall sequestration target, while other sectors are also making simultaneous contributions to the emission reduction strategy. Empirical simulation analyses were performed based on the setup above, and our results showed that 7,995,590.24 ha of plantation are required if the forestry sector is responsible for 100% of the carbon emission reduction target, which is not practical in Taiwan. If we take into account landscape factors and the government's budgetary constraints while assuming an even allocation of new plantation acreage annually between 2008 and 2020, we require 749,897.39 ha of new plantation per year in order to meet the standards of the Kyoto Protocol solely through afforestation. If we lower the forestry sector's required contribution towards carbon emission reduction down to 5%, we shall require 399,779.51 ha of new plantation in total; after considering landscape factors and the government's budgetary constraints, 37,494.84 ha of new plantation is required per year between 2008 and 2020 in order to deliver the level of contribution demanded from the forestry sector.

Similarly, when the forestry sector's required contribution towards carbon emission reduction is 1%, the social planner seeks to minimize government spending and thus requires 79,955.90 ha of new plantation in total; after considering landscape factors and the government's budgetary constraints, the social planners shall require 7,498.97 ha of new plantation per year between 2008 and 2020 in order to deliver the level of contribution demanded from the forestry sector with minimum government spending.

Taiwan's economy is still growing and thus is producing relatively high carbon emissions. It is extremely challenging to rely solely on the contribution of the forestry sector to comply with the standards outlined in the Kyoto Protocol within a short period of only 10 years (compliance by year 2020). The government must coordinate the efforts from both forestry and non-forestry sectors while making proper adjustments to our industry structure in order to achieve our target carbon emission level. Furthermore, the production values from both the agriculture and forestry sectors represented less than 2% of production from all sectors in Taiwan (Council of Agriculture, the Executive Yuan, 2008); the estimation that the Reforestation Policy and the Plain Landscape Afforestation Program contribute to approximately 4% of the reduction target set forth in the Kyoto Protocol is within our expectations. The enhancement of ARD practices (Afforestation, Reforestation, Deforestation; Article 3.3 of the Kyoto Protocol) shall become the trend for forestry sectors across the world. Compared with the energy sector, ARD not only incurs less costs during emission reduction, it also provides an interim solution that is crucial to all countries. Apart from the afforestation rewards, Taiwan should also facilitate ARD by establishing carbon volume databases to provide the basis for emission reduction. An effective implementation of ARD may also provide relief to industry restructuring.

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