

Comparison of carbon sequestration potential in agricultural and afforestation farming systems

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ABSTRACT: In the last few decades, many forests have been cut down to make room for cultivation and to increase food or energy crops production in developing countries. In this study, carbon sequestration and wood production were evaluated on afforested farms by integrating the Gaussian diameter distribution model and exponential diameter-height model derived from sample plots of an afforested hardwood forest in Taiwan. The quantity of sequestered carbon was determined based on aboveground biomass. Through pilot tests run on an age-volume model, an estimation bias was obtained and used to correct predicted volume estimates for a farm forest over a 20-year period. An estimated carbon sequestration of 11,254 t C was observed for a 189ha-hardwood forest which is equivalent to 41,264 t CO₂. If this amount of carbon dioxide were exchanged on the Chicago Climate Exchange (CCX) market, the income earned would be 821 US\$ ha⁻¹. Carbon sequestration from rice (*Oryza sativa*) or sugarcane (*Saccharum officinarum*) production is discharged as a result of straw decomposition in the soil which also improves soil quality. Sugarcane production does not contribute significantly to carbon sequestration, because almost all the cane fiber is used as fuel for sugar mills. As a result of changing the farming systems to hardwood forest in this study area, carbon sequestration and carbon storage have increased at the rate of 2.98 t C ha⁻¹ year⁻¹. Net present value of afforestation for a 20-year period of carbon or wood management is estimated at around US\$ 30,000 given an annual base interest rate of 3 %.

Keywords: Taiwan, plantation on farm land, carbon capture and storage, aboveground biomass, forest management

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Introduction

Land use has changed around the world in the last few decades. Many forests have been cut down to make room for cultivation and to increase food or energy crops production in developing countries. One example is the Ex-Mega Rice Project (EMRP) in Indonesia where an area of around 146 million ha of peat swamp forest was converted to rice (*Oryza sativa*), palm (*Elaeis guineensis*)-oil production and settlement in the 1980s (Galudra et al., 2010). In addition, many agricultural lands are left fallow and not used for food production in some developed countries due to local development and free trade agreements. Agricultural lands are believed to be a major potential carbon sink to absorb large quantities of carbon if trees are reintroduced with judiciously managed crops and/or animals (Albrecht and Kandji, 2003). Thus, the importance of agroforestry systems (AFS) is the land-use management. AFS has been proved to improve broader-level ecosystem services, including water quality enhancement, soil improvement, and carbon sequestration. The relative newness of research in environmental quality and AFS will pose additional challenges in the future, including the determination of tree-biomass, establishment of standardized norms in soil sampling depth, and resolutions for issues regarding limits of fixed-effect models (Nair, 2011).

The Kyoto Protocol is an international environmental treaty and requires ratified countries to commit

themselves to an appropriate reduction of greenhouse gases (GHG), which contributes to global warming and potentially impacts human society in many ways. In contrast to reduce GHG by industrial sectors, afforestation on fallow farm land has obviously become an important alternative method to expand the potential pool of carbon stock in terrestrial ecosystems. The Forestry Bureau in Taiwan (TFB) adopted an afforestation policy to encourage farmers to plant trees on fallow land starting 2002, particularly on unused crop and sugarcane farms. To answer Nair's statements in 2011, the main purpose of this paper is to integrate the allometric parameters-based single tree growth model and stand structure model in order to achieve three main objectives: measurement of the potential aboveground biomass and carbon stock of afforestation hardwood forest, evaluation of the carbon sequestration ability of the afforested farming system and the traditional paddy/sugarcane farming system, and prediction of the productivity and economic potential of hardwood farms.

Materials and Methods

Figure 1 shows a flowchart of the methods used in this study. In this figure, a crop farming system is also included to enable economic comparison of crop farming and forestry management. This study is only concerned with the present value of woods and/or crop products and the market value of carbon. A detailed cost/benefit

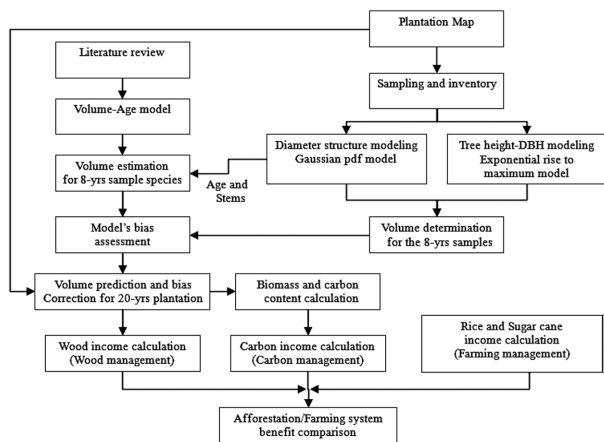


Figure 1 – Analytical flowchart for evaluating carbon sequestration associated with afforestation and food production.

analysis, including factors such as the opportunity cost of land use and marginal benefits are not considered.

Site description and sampling design

The studied afforested area has 188.59 ha and is located in Baihe Township, Tainan City, in southern Taiwan which is centered at 23°19'47" N and 120°25'44" E. The average altitude of the study site is 37 m a.s.l and average annual precipitation and temperature are 1759.74 mm and 23.5 °C, respectively. Summer is usually rainy in this area.

More than ten tree species at the farm (Baihe Farm) are planted in the early spring of 2002. *Fraxinus formosana* and *Melaleuca leucadendron* are the major species. The plantation area of these two species is 48.23 ha and 32.29 ha respectively. They occupy 43 % of the total area of the farm. Some other minor species are also present, for example *Terminalia boivini*, *Melia azedarach*, *Zelkova serrata*, *Camphora formosana*, and *Liquidambar formosana*, whose plantation area varies from 3 to 10 ha. Because the shape and size of the afforested regions in the farm are irregular, the sample plots used to make the forest inventory have variable dimensions of 50 × 50 m, 30 × 30 m, and 20 × 40 m representing areas of 0.25 ha, 0.09 ha, and 0.08 ha respectively. As a result, 24 plots accounting for 5.03 ha of the plantations were included in the forest inventory. The sampling inventory was carried out during Jul., 2008. The trees in the study site were considered to be eight years old after taking into account complete growing seasons and seedling age.

Calculation of individual volume

This study developed specific volume models (Eqns. 1-3) for *Fraxinus formosana*, *Terminalia boivini* and *Melia azedarach*, respectively, based on the inventory data. The trunk volume for other species was determined using Eqn. (4) which was suggested for general use in determining the volume of broadleaf trees. Mathematically, tree volume is calculated using a cylindrical

model, with a shape factor (f) of 0.45 representing the taper coefficient of the broadleaf tree stems. The parameters DBH and H represent the tree diameter at breast height (in centimeters) and total height (in meters) of a tree. The volume models were used to determine a cubic meter unit of stem volume (V).

$$V = 0.0000280927 \times \text{DBH}^{1.231} \times H^{1.693} \quad (1)$$

$$V = 0.0000199357 \times \text{DBH}^{1.902} \times H^{1.250} \quad (2)$$

$$V = 0.0000438384 \times \text{DBH}^{1.897} \times H^{0.965} \quad (3)$$

$$V = \frac{\text{DBH}^2 \times \pi}{40000} \times H \times f \quad (4)$$

Estimating volume growth stock in an eight year old forest stand

Estimating plantation volume involves a three-step process. First, the DBH structure or frequency (F) of the sample plots were fitted to a Gaussian PDF (probability distribution function) model (Eqn. 5) to derive a model representing the frequency of the stem diameter per hectare. Second, the DBH values were regressed with the total height of the sample trees in an "exponential rise to maximum" model (Eqn. 6). Third, the volumes of individual tree stems were determined using Eqns. (1-4) and summed to obtain the total stock volume per hectare for each species. Finally, the total stock volume of the afforested area was calculated based on the plantation area for each species.

$$F = a \times \exp \left[-0.5 \left(\frac{x - x_0}{b} \right)^2 \right] \quad (5)$$

$$H = y_0 + a \times (1 - \exp(-b \times x)) \quad (6)$$

Predicting growth stock in the forest stand over 20 years

An age-volume estimation model (Eqn. 7) that uses tree age (A) as the regressor was used to predict the stock volume for an eight year old forest (V_m). The estimate was then used to derive an adjustment factor (E) for the age-volume model. This factor indicates the estimation bias when using the age-volume model in the prediction of volume stocks of the forest stand. So, the volume estimate should be adjusted so that it approaches the real value using the factor E . In this way, the volume estimate for the 20 year old hardwoods was determined. A survival probability of 70 % after 20 years was assumed in comparison to the original plantation density. In Eqn. (8), the percentage adjustment factor E can be determined using the measured volume (V_r) and the estimated volume (V_m) obtained from the age-volume model.

$$V_m = -0.00009 + 0.0047 \times A + 0.00008 \times A^2 \quad (7)$$

$$E(\%) = \left(\frac{V_m - V_r}{V_r} \right) \times 100\% \quad (8)$$

Aboveground Biomass and carbon content estimation

The carbon content of the forest was estimated using Eqn. (9), which is a modification of the IPCC (Intergovernmental Panel on Climate Change) method (Penman et al., 2003) that has been successfully applied to carbon estimation by Lee et al. (2000), Lin et al. (2002), Lee et al. (2004), and Wu et al. (2005). In Eqn. (9), the total carbon in aboveground biomass (C) is the product of volume (V , $m^3 ha^{-1}$), basic wood density (D), biomass expansion factor for the conversion of volume to aboveground tree biomass (BEF_2), multiplied by the carbon fraction of dry matter (CF , tonnes C).

$$C = (V \times D \times BEF_2) \times CF \quad (9)$$

The total forest volume was determined following the method used by Brown et al. (1986), Sedjo (1989), and Winjum et al. (1998). This study used a 1.65 expanding coefficient for restoring whole volume. The aboveground biomass was determined by multiplying the volume by the wood density. Wood densities for *Cinnamomum camphora*, *Swietenia macrophylla*, *Zelkova serrata*, *Melaleuca leucadendron*, *Melia azedarach*, *Fraxinus formosana* and *Terminalia boivinii* are $0.395 g cm^{-3}$, $0.490 g cm^{-3}$, $0.687 g cm^{-3}$, $0.600 g cm^{-3}$, $0.498 g cm^{-3}$, $0.664 g cm^{-3}$ and $0.421 g cm^{-3}$. An average density of $0.536 g cm^{-3}$ was used for

the other hardwoods growing at Baihe Farm since the individual wood densities of these woods was not available in the literature. Lin et al. (2002) demonstrated that some hardwoods have dry biomass carbon fraction (CF) ranging from 45 -48 % and suggested an average of 46.91 % as being suitable for application. Following this suggestion, this study used 46.91 % in determining the carbon content of the forest.

Results

Diameter structures and height models of the Baihe Farm Forest

The study site yielded 24 samples of four dominant tree species, namely *Fraxinus formosana*, *Melia azedarach*, *Terminalia boivinii*, and *Melaleuca leucadendron*. A Gaussian probability distribution function was applied to fit the DBH data for each of the dominant species. Figure 2 shows the fitted Gaussian model for each species. An ANOVA test was applied to examine the estimated coefficients. Each coefficient is significant at the 0.01 probability level, indicating that the hardwood forest in the cultivated land exhibited a normal diameter distribution. Additionally, the total tree height (y) is regressed with the DBH (x) to fit an exponential growth model to represent the influence of diameter growth on height growth. Results are shown in Figure 3 and listed in Table 1. The R^2 of the regression models suggests that the models are able to explain 50-68 % of the variation in tree height.

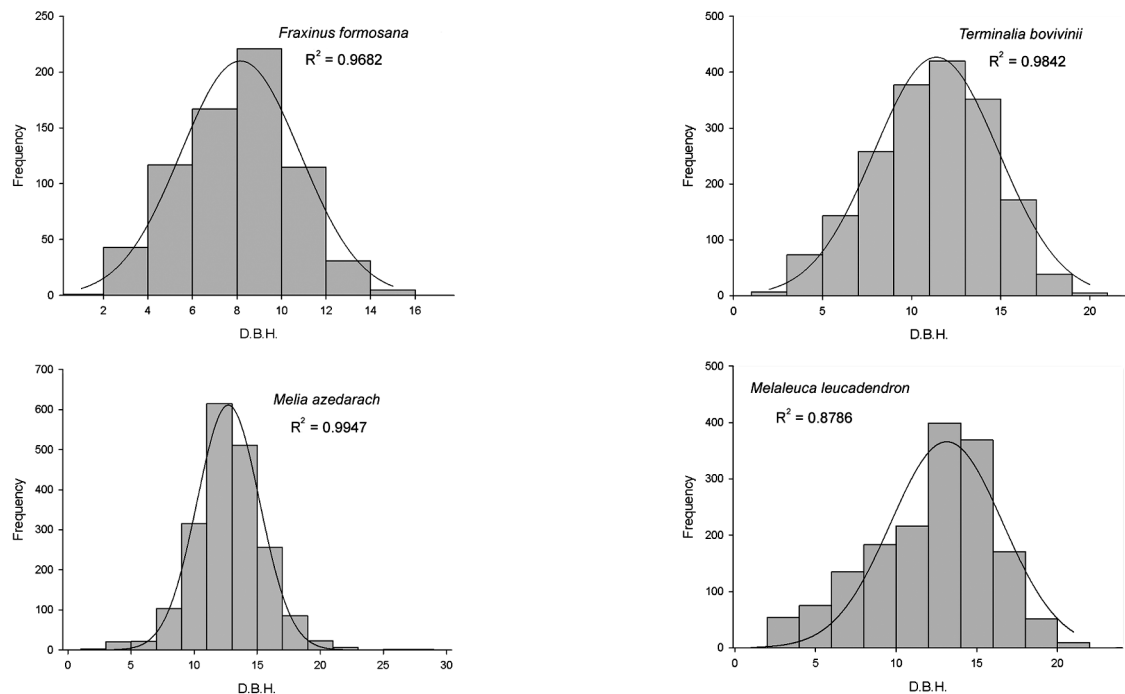


Figure 2 – Diameter distribution of the stands for the four sampled major species in Baihe Farm forest

Sample data from the four dominant species and additional sample plots of the remaining six species were integrated and re-fitted to obtain a DBH Gaussian PDF model for Baihe Farm forest, and furthermore were fitted with an exponential growth model (Figure 4). The integrated regression model has a coefficient of determination of 0.4900 (Table 1) and testing demonstrates the regression coefficients to be significant at 0.05 probability level.

Estimation bias of the age-volume model of Liu and Wu

The total volumes of the inventoried four species (*Fraxinus formosana*, *Melia azedarach*, *Terminalia bovininii*,

Melaleuca leucadendron) stands was 218.81 m³, and averaged 54.70 m³ ha⁻¹ (Vr). An age-volume model was used to estimate individual stem volume taking tree age as a reference. This study used the total number of individual stems as a multiplier N to determine a unitary plantation volume using the age-volume model (Vm) where N estimates for each of the selected species are determined by their Gaussian PDF models. Consequently, Vm was considered to be an underestimate with an error E (%) of 4.53 % (Table 2).

The estimation error is further assessed on the integrated dataset that contains four dominant species and an additional six inventory species in Baihe Farm forest. All samples of the ten species were pooled and then re-

Table 1 – Tree height models for the tree species in Baihe Farm forest.

Species name	Equations	R ²	P-value
<i>Fraxinus formosana</i>	$y = 9.5054(1-\exp(-0.1558x))$	0.4958	<0.0001
<i>Melia azedarach</i>	$y = -3.8192+16.1710(1-\exp(-0.2148x))$	0.6277	<0.0001
<i>Terminalia bovininii</i>	$y = 13.4173(1-\exp(-0.0997x))$	0.6765	<0.0001
<i>Melaleuca leucadendron</i>	$y = 7.9809(1-\exp(-0.1462x))$	0.5511	<0.0001
The other species	$y = 13.055(1-\exp(-0.1099x))$	0.4900	<0.0001

Table 2 – Estimation bias of the model based on the 8-years samples for different species.

	Four major species	Pooled data
Vr: Unitary volume stock (m ³ ha ⁻¹)	54.70	58.11
Vm: Age-volume model estimation (m ³ ha ⁻¹)	52.22	52.52
Bias (%)	-4.53	-9.62

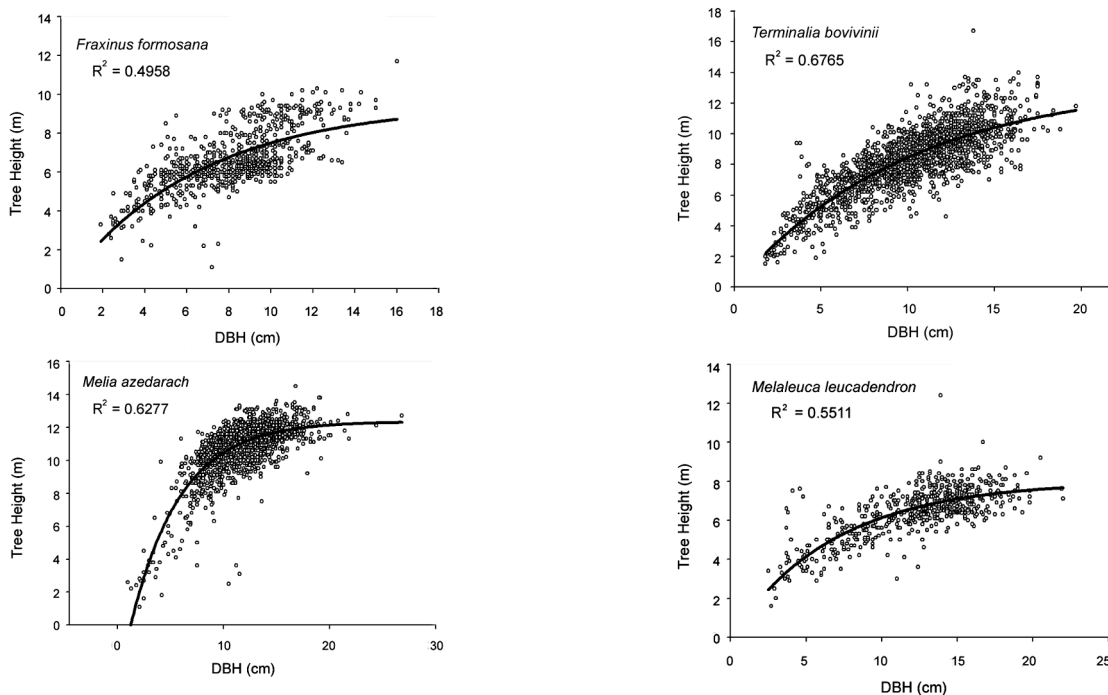


Figure 3 – Empirical exponential DBH (diameter at breast height)-height models of the stands for the four chosen dominant species in Baihe Farm forest. The P-value of the regressions is less than 0.0001 indicating that the models are statistically significant and could be applied for height prediction using DBH.

fitted using a Gaussian diameter PDF model. The stem estimation of the proposed model in the sample plots was 1,232 and the volume estimate was 52.52 m³ ha⁻¹. The estimate was underestimated with an error or bias of 9.62 % (see Table 2). This study largely focused on estimating the stock volume of forest cultivated on a farm over a period of 20 years. Because numerous tree species are growing on the farm, the pooled diameter distribution model should be appropriate. This study thus adopted an adjustment coefficient of 1.0962 to represent the potential expansion of the predicted volumes, biomass, and carbon contents.

Evaluation of afforestation carbon economy and crop economy

Afforestation carbon benefit

Farmers who afforest cultivated farmland will be supplied with seedlings free of charge. Afforestation costs include seedling packing, transportation from the nursery to the planting site, soil preparation, labor for distributing seedlings among individual planting holes, planting, and weeding, and these expenditures were estimated based on the data for the plantation of BAT-TAIWAN (British American Tobacco Taiwan) in Nantou County, Taiwan. The total cost comes to US\$ 9,403.01 (hereafter the monetary amounts will be given in US dollars). The estimated trunk volume for the entire area (188.59 ha) of Baihe Farm is 24,932.64 m³; this quantity was magnified up to 27,331.15 m³ together with the 9.62 % underestimation bias of the age-volume model.

Accordingly, aboveground biomass was determined by multiplying the whole volume expansion coefficient (BEF₂) 1.65 by the wood densities (D) for the individual species; carbon content sequestered in the Baihe Farm forest was determined to be 11,253.80 metric tons over a 20 year period. This quantity of carbon is identical to 41,263.93 t CO₂ which can be obtained by multiplying the metric tons of carbon with the CO₂ conversion coefficient of the molecular mass percentage of carbon and oxygen (Table 3). Though trees (C₃ plant) can sequester more significant carbon in the deep soil profile than C₄ plants (Nair et al., 2007), the below-ground biomass of farm forest was not counted in the carbon determination because carbon markets do not yet recognize below-ground biomass in the estimation of storage for carbon credits.

If all the carbon to be sequestered in a 20 year management period is exchanged in the CCX CFI carbon market, the income realized will be 820.51 \$ ha⁻¹. Considering both costs and income, including subsidies and carbon trading, the profit per hectare of afforestation with hardwoods on Baihe Farm was \$ 43,036.61 for the CCX CFI carbon markets.

Profit from agriculture crops

The aboveground biomass of rice and sugarcane is used usually as soil fertilizer or fuel; consequently the sequestered carbon will be released completely. According to official statistics from the Agriculture and Food Agency in the Council of Agriculture, Taiwanese rice farmers typically harvest two crops each year, with

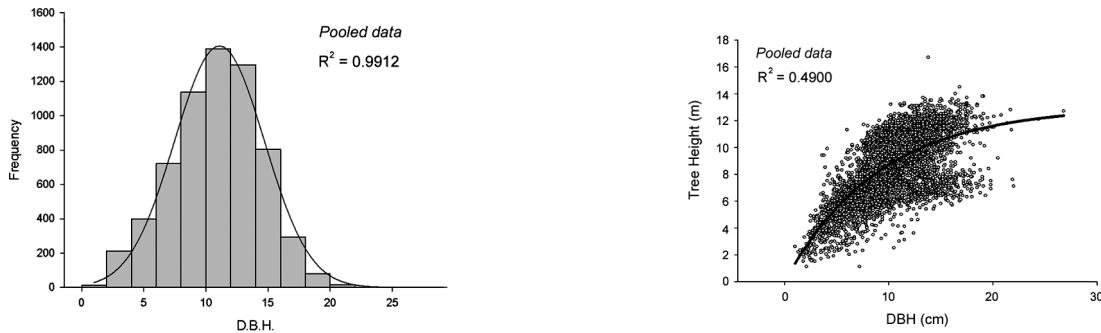


Figure 4 – Diameter distribution and DBH (diameter at breast height)-height model of the pooled data for the species at Baihe Farm. The P-value of the pooled data regression model is less than 0.0001. It indicates that the pooled model is statistically significant and could be applied for height prediction using DBH for the minor species in the farm forest.

Table 3 – Total carbon sequestration for the 188.59 hectare 20-years hardwood plantation of Baihe Farm.

Components	Trunk volume	Whole volume	Dry biomass	Carbon contents	
				(tonne or t C)	t CO ₂
	m ³		tonne		
Model estimation	24,932.64	41,138.85	21,884.86	10,266.19	37,642.69
Bias adjustment	2,398.52	3,957.56	2,105.33	987.61	3,621.24
Determined	27,331.15	45,096.41	23,990.19	11,253.80	41,263.93

*Averaged carbon management efficiency is 2.98 t C ha⁻¹ year⁻¹ and the farm forest carbon storage density is 59.67 t C ha⁻¹; Compared to the urban forest carbon storage density ranging from 25.1 to 53.5 t C ha⁻¹ in the USA (Nowak and Crane, 2002), intensively managed afforestation hardwoods on farm land can effectively promote carbon sequestration.

each crop representing production costs of US\$ 3,255.90 ha⁻¹ and income of US\$ 3,358.13 ha⁻¹. Consequently, rice farmers average a profit of just US\$ 204.46 ha⁻¹ from their crops, representing just US\$ 4,089.20 ha⁻¹ over 20 years of rice farming. Sugarcane needs 12 or 18 months growing time to mature to sugar production size during the first or the second generation farming, and each generation produces gross material totaling 78 metric tons ha⁻¹. Over 20 years, farmers will harvest 16 generations, producing 1,248 metric tons of gross materials per hectare. According to TSC just 10 % of this gross material can be made into sugar. The spot price of sugar was US\$ 0.80 kg⁻¹ in 2001. Therefore, the income for a single term cane crop is US\$ 6,221.49 ha⁻¹ meaning that after deducting production costs of US\$ 2,350.75 ha⁻¹, cane farmers achieve a profit of US\$ 3,870.74 ha⁻¹ per term or US\$ 61,931.84 ha⁻¹ over 20 years of continuous farming. The potential benefits of the afforestation system in comparison to the cropping system over a 20 year period are shown in Table 4.

Discussion

Productivity and economic potential of hardwoods farming system

The predicted volume productivity of hardwood afforestation at Baihe Farm is approximately 7.2 m³ ha⁻¹ year⁻¹. According to the timber logging database of the Taiwan Forestry Bureau, there were 67.38 ha (clear cutting) and 0.22 ha (selection cutting) of hardwood forest harvested from southern Taiwan in 2007, denoted as the South Taiwan Hardwood case (abbreviated STH). These represent a total timber yield of 2,861.56 m³. The age of the logged hardwoods is assumed to be 20 years based on the forest lifespan required by the afforestation policy of TFB, and the fact that mountainous hardwoods have a productivity of 2.1 m³ ha⁻¹ year⁻¹. The results of this study demonstrate that farm afforestation productivity is approximately three times that of hill and mountain hardwood plantations. Baihe Farm is located in Tainan City, one of the main sites for rice and sugarcane production in Taiwan, and its site quality is considered much better than that of mountainous and hill sites. Farm afforestation hardwoods thus have a higher potential productivity than hill/mountainous hardwoods.

From the STH case, the income from hardwood production is approximately US\$ 89.87 m⁻³. Although no cost data is available for the STH case, such data

is available for another data set that is the production cost of timber logging, gathered from all of the private hardwood plantations in Taiwan during 2007 (denoted as case WTH). This case involved a logged volume of 3,366.43 m³. Cost items listed in the WTH data set are considered for cost correction, with the exception of the woodland path cost, since the road network on the flatland areas of Taiwan is well developed. Consequently, the adjusted cost is US\$ 183.72 m⁻³ and income is US\$ 200.60 m⁻³, and thus the total benefit can be calculated as US\$ 16.88 m⁻³, representing approximately 8.4 % of total income. This percentage is employed as a coefficient of forestation benefit and applied to determine the benefit of growing forest in the STH case. Accordingly, it is estimated that TSC, which manages the Baihe Farm hardwood forest, will achieve a profit of US\$ 7.55 per cubic meter volume of wood with the total profit ranging from US\$ 188,240 to 206,350. A median value of US\$ 197,296 can be considered as a generalization, assuming the trees grow for 20 years.

In considering the carbon sequestration rate (CSR), the Baihe farm hardwood forest has a potential of 2.98 t C ha⁻¹ year⁻¹, equivalent to 10.93 t CO₂ ha⁻¹ year⁻¹ based on a 20-years growing period. This amount of aboveground carbon is less than 5.02 t C ha⁻¹ year⁻¹ (18.41 t CO₂ ha⁻¹ year⁻¹) the CSR of farm forest but greater than 2.52 t C ha⁻¹ year⁻¹ (9.24 t CO₂ ha⁻¹ year⁻¹) the CSR of tubestock revegetation forest in Victoria, Australia. Carbon sequestration rates for USA cases are available from CCX reforestation carbon accumulation tables, which can be found in a landowner's guide to carbon sequestration credits by Current et al. (2007). In a densely planted forest with more than 250 stems per acre, the carbon sequestration rates of 20 year old mixed hardwoods in Northern Plains, bottomland hardwoods in Central States, mixed hardwoods in Corn Belt, and bottomland hardwoods in South Central are 5.76, 5.33, 10.80, and 4.89 t CO₂ ha⁻¹ year⁻¹ respectively. Additional research such as that investigating a hybrid poplar forest (Updegraff et al., 2004) and a coniferous-deciduous mix afforestation forest (Niu and Duiker, 2006) have carbon sequestration rates around 8.98 and 9.53 t CO₂ ha⁻¹ year⁻¹ after 20 years. Carbon sequestration rates of forest in New Zealand can be found in work by Hollinger et al. (1993), Tate et al. (1997), Scott et al. (2000), and Trotter et al. (2005).

The CSR varies from 8.10 for 40 year old afforested/reforested pasture lands, 9.52 for 25 year old scru-

Table 4 – A potential benefits comparison to the cropping system and afforestation system in a 20-years continuous period.

Farming systems	Cost	Income	Benefit (US\$ ha ⁻¹)		
			Single term	Terms in 20 years	Total
	US\$				
Afforestation carbon management	9,403.01	52,439.62	43,036.61	1	43,036.61
Afforestation wood management	9,403.01	52,665.27	43,262.26	1	43,262.26
Rice cropping	3,255.90	3,358.13	102.23	40	4,089.20
Sugarcane cropping	2,350.75	6,221.49	3,870.74	16	61,931.84

bland, to $18.33 \text{ t CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$, for planted forests. By comparing these observed data, it can be seen that farm afforestation in Taiwan has a relatively good potential for increased carbon sequestration rate. This value is very close to the $3.00 \text{ t C ha}^{-1} \text{ year}^{-1}$ growth rate of the aboveground standing stock estimation model described by Marland and Marland (1992). Although afforested hardwoods have a 3.00 annual carbon sequestration rate, this is still well short of the $8.50 \text{ t C ha}^{-1} \text{ year}^{-1}$ of an eight year old bamboo stand of *Phyllostachys pubescens* in Japan observed by Isagi et al. (1997). It seems that growing bamboo is an easier way to meet the carbon sequestration goal of $13.00 \text{ t C ha}^{-1} \text{ year}^{-1}$ as suggested by Hiroshima (2004) for Japanese plantation forests.

Net contribution of paddy/sugarcane farming system to carbon sequestration

Carbon sequestration of farm crops is a major concern of this study. Fire is generally a simple tool for agricultural management. It is used very often in many countries particularly for the development of shrub forest/savanna/cerrado. While the conversion of native land cover through slash and burn followed by cultivation results in a decrease in carbon stocks and an associated increase in CO_2 emissions (Detwiler, 1986; Brown and Lugo, 1990; Lal, 2003; Franchini et al., 2007; Carvalho et al., 2009). In Taiwan, farmers sometimes burn rice straw into ash or more commonly, bury it directly in the soil to provide nutrition for the next growing season. Burning rice straw will directly release sequestered carbon into the air, strongly influence air quality, and will cause a danger to traffic if it is carried out near roadways. Rice straw burning is thus prohibited by law in Taiwan. An alternative method involves burying the straw under a layer of earth and allowing it to **degrade naturally**. Burying straw increases the quantity of organic matter in the soil, saves labor and other costs, and increases the yield of the next rice crop. This not only avoids the problem of air pollution, but also helps to improve soil nutrients. As indicated by Guo (2005), following three years of continuously burying straw in a paddy field, the organic matter contents of the soil will increase by 2.1-2.7 %, increasing quantities of essential chemical elements such as phosphorus, potassium, calcium, and iron. Furthermore, burying straw improves soil granule structure and physical properties. As a result, rice production will be increased by 5-10 %. No matter what the rice straw will be burned or buried, the sequestered carbon will be released.

Sugarcane pulp is the biomass remaining after crushing sugarcane stalks for sugar production. According to the methods of sugar production used by TSC, sugarcane pulp is frequently used as a primary fuel source for sugar mills. When burned in quantity it produces sufficient heat energy to supply all the needs of a typical sugar mill, with energy to spare. Meanwhile, the ash can be used as soil fertilizer. This also leads the release of carbon. This study thus concludes to the simi-

lar point assumed by Shively et al. (2004) that little crop carbon is conserved and no carbon economy is available for both rice and sugarcane cropping systems. Concerning about the belowground biomass, suitable agricultural practices are able to increase soil carbon stocks by around 1.5 time (Carvalho et al., 2009). Even though the below-ground carbon could be increased by appropriate tillage operation, the soil organic carbon content in forest is significantly four times higher than agroecosystem (Singh and Ghoshal, 2011).

Decision making related to feasible afforestation management goals

Economic benefits as top priority

In the case of the study site, Baihe Farm, the plantations cover 188.59 hectares and grow more than ten hardwood species. In the case where a farm owner wishes to become involved in wood management, and the benefits can be calculated as $52439 - 9403 = 43036$ dollars for implementing an afforestation policy (see Table 4), TFB regulations require that afforested forests must be continuously managed for at least 20 years and the owners can determine the use of the forest following this period of regulation growth. This study thus sets 20 years as the rotation age of the hardwoods grown on the study site, providing the owner with an additional benefit from wood harvesting; based on estimates of trunk volume, the average value is expected to be \$197,296. On average, a profit of \$1,046.16 can be achieved from one hectare of farmland converted to forest. Summing these two amounts, the farm owner will achieve a total benefit of US\$ 43,262 ha^{-1} over a 20 year management period. In comparison, if the farm owner grows rice the economic benefit over 20 years will be US\$ 4,089 ha^{-1} and for sugarcane US\$ 61,932 ha^{-1} . Clearly, growing rice paddies is far less profitable than afforestation, while growing sugarcane is 1.4 time more profitable. Net present value (NPV) is used in capital budgeting to analyze the profitability of an investment or project. The prelisted future values of forest management and food production can be calculated at the base of 0.03 discount rate with a NPV level of US\$ 30,390 for wood management, US\$ 30,265 for carbon management, US\$ 18,091 for sugarcane production, and US\$ 3,042 for rice production.

At the study site, the owner grows various species for landscape gardening use, including *Terminalia bovivinii*, *Cinnamomum camphora*, and *Bischofia javanica*. Generally, trees used for landscaping are sold individually and sold at a higher price. Thus, we would recommend that landowners grow special trees suitable for garden use, since they offer a more profitable method of afforestation than growing trees for wood production.

Carbon trading management as top priority

The carbon market allows foresters to transfer the carbon conserved in their trees to companies needing an equivalent number of carbon emission credits or al-

lowances, and/or that need to purchase credits to offset increased emissions. Prices for credits on the carbon market have varied greatly over time. In this study, the carbon price is determined 3.75 \$ t⁻¹ CO₂ using the CCX CFI annual average price in 2008, the forest inventory year. During a 20 year period of forest management, Baihe Farm forest will produce dry biomass totaling 23,990.19 tonnes. Consequently some 11,253.80 metric tons of carbon, equivalent to 41,263.93 t CO₂ in the air, will be sequestered and conserved in the woods. If this quantity of carbon is exchanged on the CCX carbon markets, it will have a value of approximately US\$ 154,740. The average benefit of carbon trading is thus US\$ 820.51 ha⁻¹ when the forest reaches 20 years of age. Including the afforestation subsidy, the total benefit becomes US\$ 43,036.61 ha⁻¹ over a 20 year management period. The total benefit thus closely approaches that of wood production which equals US\$ 43,262.26 ha⁻¹, but is less than growing sugarcane.

According to the LULUCF (land use, land use change and forestry) principles for ensuring environmental integrity of the Kyoto Protocol, there are some important accounting rules that must be satisfied. Some examples of the rules are: i) continuity of responsibility must be ensured, ii) emissions and removals should continue to be reported and accounted for when they occur, iii) asymmetries in accounting should be removed. Thus, there should be no swapping of sinks or forest cutting if afforested forests are to be used for carbon trading. Carbon trading cannot occur if the forest is managed for timber cutting. The stock volume of afforested forest is continuously increased hence enlarging the afforestation carbon pool. It therefore results in an increased amount of carbon trading in the future.

Seeking environmentally friendly management methods

Results of this study demonstrate the benefits of afforestation of cultivated land over 20 years involving both wood-production and carbon trading. However, without government subsidies, afforestation management on cultivated land is impossible for farmers owing to the limited US\$ 820.51 ha⁻¹ benefit available over a 20 year timeframe. Even if farmers obtain no subsidies for the 20 years following the initial afforestation, the forest remains environmentally valuable because of its ability to conserve wood carbon or act as a carbon reservoir. Afforestation is also a good option as it is inevitable that an increasing amount of cultivated land will cease to be utilized for cropping under the combined impact of WTO entry and an ageing agricultural labor force.

As is widely postulated, growing sugarcane is environmentally beneficial. Although carbon conservation cannot be achieved during sugar production, burning sugarcane biomass in quantity produces sufficient heat energy to fully supply the needs of a typical sugar mill. Burning sugarcane biomass thus offers an effective means of reducing energy use and hence carbon dioxide

emissions. Farm afforestation may also result in a forest landscape which might offer highly attractive scenery suitable for human recreation. In addition to direct carbon storage, farm forest close to urban areas can also help to reduce energy consumption and further decrease carbon emissions. Farm forest biomass will continuously increase and might enlarge the potential amount of carbon storage. Moreover afforested hardwoods might induce a significant contribution of biodiversity. These factors all serve as a positive recommendation for farm afforestation carbon management for the farmer who is trying to reduce levels of crop production. Soto-Pinto et al. (2010) addressed agroforestry systems such as silvopastoral systems, improved fallow, Taungya and coffee (*Coffea* spp.) (polyculture-shade coffee and organic coffee) systems which have good potential to sequester carbon via growing trees. If burning is avoided in agroforestry systems, it could also contribute to carbon sequestration and reducing emissions. Peichl et al. (2006) also addressed silvicultural management and suggested that this method can contribute to the quantity of carbon accumulation in agroforestry. It is therefore suggested that agrosilvicultural systems consisting of planting trees in croplands (Nair, 1993) might bring benefits to both farming systems and afforestation systems.

Combining farming with forestry creates some additional social benefits such as high aesthetic value and biodiversity of landscape which were not the original objectives designated by the farmers for the rural area. This brings the "farm forest" itself into a much safer situation reducing the probability of anthropogenic interferences and stochastic events (forest fires or wind storms). By providing recreational facilities and landscape enhancement (ranging from cooling effects and air purification, to attraction of bird species), the forest will in turn be appreciated by local citizens who are likely to play a role in its protection (i.e. against forest fires). In addition a more mature forest will be less prone to damage by typhoons that frequently damage trees in Taiwan. With the inherent ability of the biophysical systems, the carbon sequestration rate will continuously increase in the commitment period of emission reduction. It is known that forests do not sequester carbon at the same rate during their lifespan. The forest will start slowly, and eventually taper off once the forest has matured, and finally the old matured trees will re-emit the carbon when they die and decompose. Harvesting is considered as an emission activity by LULUCF principles. Therefore, it is necessary to propose a suitable management framework for "farm forest" regeneration to ensure the environmental integrity of the removal of CO₂ from the atmosphere.

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