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Economic effects of the biochar application on rice supply in Taiwan

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Abstract: The objective of the study is to analyze the economics of the bio-energy production for Taiwan in terms of the bio-energy production, social welfare and crop yield increase under the conventional bio-power, ethanol and pyrolysis. The effects on rice production patterns are also examined for the fast and slow pyrolysis plus the biochar application. In addition to adopting the mathematical programming model (Modified Taiwan Agricultural Sector Model) in the analysis of the bio-energy production and the crop cultivation patterns, the study further employs a nonparametric kernel regression model to forecast the increased benefits of rice from using biochar under various scenarios. With the biochar application, Taiwan's rice production could increase ranging from 6308 to 38 118 tons annually, depending on the pyrolysis type and the plant location. The results indicate that the biochar utilization can potentially increase social benefits if rice is planted. The net increase of farmer›s and the environmental revenues can achieve up to NT$ 419 400. Moreover, we find that farmers should give priority to the improvement of nutrient saving to make higher benefits. Second, the total benefits could be improved if the seed use is efficient and harvesting and transporting costs for the energy crop and processing and the hauling cost of biochar are lower. Simulation results indicate that Taiwan benefits from the bio-energy production in terms of energy security, farmers revenue, social welfare and rice supply. The results show that, in general, pyrolysis plus the biochar application not only increase the domestic renewable energy supply but also enhance the farmers' and environmental revenues significantly.

Key words: bio-ethanol, energy security, food supply, nonparametric analysis, pyrolysis

Most of the Taiwan's energy is imported and as a result, Taiwan is vulnerable to high energy prices and market distortions in the world energy market. Therefore, the lack of energy security is a serious problem facing Taiwan. In addition to the domestic renewable energy supply, the development and application of renewable energy bring a direct benefit to the world: the climate change mitigation. The climate change is an emerging challenge facing the world. The annual report of the Intergovernmental Panel on Climate Change (IPCC) indicates that the Earth is warming due to the anthropogenic emissions of greenhouse gases (IPCC 2007). Such warming would have consequences ranging from the increased desertification, a rise in ocean level and the possible increased occurrences of hurricanes, all of which can result in enormous damages to Taiwan. In addition to the threats of energy insecurity and the climate change, one serious problem facing Taiwan is that the farmers usually suffer from a low income because the agricultural sector is a less profitable industry where people engaged in this industry usually suffer from a lower income. For this reason, Taiwan has been helping its rural areas and enhancing the standard of the farmers' living for many years. However, due to the historical, geographical, and climatic reasons, the farmers' living standards have not been improved significantly. The government subsidy does help to increase the people's living standards, but it is not a sustainable way. In order to enhance the farmers' sustainable incomes and to improve sustainability of the future development, it is necessary to make changes to the existing agricultural production patterns. The existence of bio-energy seems to be a potential choice changing this situation because bio-energy utilizes agricultural commodities (crops, residuals or wastes)

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to produce renewable energy and to combat the climate change. Among the available bio-energy alternatives, the pyrolysis and biochar application have been attracting great interests because it not only brings clean energy but also stores carbon from the atmosphere (carbon negative property), increases the crop yields and enhances the irrigation and fertilizer efficiency (Lehmann et al. 2003; Lehmann 2007; McCarl et al. 2009; Kung et al. 2013). Because of these properties, the pyrolysis and biochar application might be one attractive bio-energy alternative. This study focuses on the economics of the bio-energy development for Taiwan in terms of the bio-energy production, social welfare and the crop yield increase. This study makes contributions by exploring not only the competition between the alternative bio-energy technologies, but also the response of the Taiwan's rice cultivation under the pyrolysis and biochar application. This study examines that the potential changes on the rice planted hectares when biochar is hauled back to the rice field. The paper aims to provide useful information on how the biochar utilization may alter the current rice cultivate activities, on a partial equilibrium basis. Besides, an econometric analysis is used to examine how the biochar application influences the economic outcomes of the rice cultivating activities as well as the environmental benefits from the reduction of the carbon dioxide emission in Taiwan. The results will be useful for the policy analysis of the government expenditures on the bio-energy development, the net GHG reduction and the associated GHG trading mechanism, estimation of the farmers' income and the quantity supply of various forms of bio-energy. The study also provides information about whether the pyrolysis and biochar application could lead to a more sustainable environmental system for future generations without any great sacrifices from the current generations.

LITERATURE REVIEW

The increasing energy use and carbon dioxide (CO_2) emissions from fossil fuels make switching to the low-carbon fuels a high priority. Exploring new energy sources that enhance the energy security and sustainability is another interest. Because bio-energy is one of the substitutes that meets these needs, it has been studied intensively and eventually, a substantial amount of bio-energy is produced in the United States and Europe. Some reports claim that we need to be careful to avoid unintended consequences of bio-fuels, that the increasing use of bio-fuels will actually increase the carbon dioxide emissions resulting in deforestation and a sudden major shift in the land use (Fargione et al. 2008; Searchinger et al. 2008). Fargione et al. (2008) mention that whether bio-fuel production is a potential low-carbon energy source depends on how it is produced.

Among the bio-energy alternatives, electricity is somewhat better than the ethanol in terms of the GHG emission offsets. McCarl (2008) shows that the emission offset rates for electricity are more than that for ethanol because the feedstock can be burned with a little transformative energy needed at the processing site. He shows that co-firing generally has offsets because the hauling distances are shorter as lower feedstock volumes are required and because of the presence of coal which increases the feedstock heat recovery. In addition to the conventional bioelectricity, pyrolysis is a potential way for the bio-energy production. Pyrolysis means to heat the biomass in the absence of oxygen and it has several forms, depending on the pressure, the heating time and the temperature during the process. The fast (slow) pyrolysis involves a thermal decomposition process that occurs at moderate temperatures with a high (low) heat transfer rate to the biomass particles and a short (long) hot vapour residence time in the reaction zone. The rate of the extent of the decomposition of biomass depends on the process parameters of the pyrolysis temperature, the biomass heating rate and the pressure (Bridgwater 2005; USDOE 2005).

In general, the slow pyrolysis yields more biochar and less bio-oil and biogas than the fast pyrolysis. Wright et al. (2008) indicate the fast pyrolysis yields about 15% biochar, 70% bio-oil and 13% biogas while Ringer et al. (2006) indicate that under the slow pyrolysis, about 35% of the feedstock carbon ends up as biochar, 30% as bio-oil and 35% as biogas. However, the yields and properties of the generated liquid product (and the solid product) depend on the feedstock, the process type and conditions, and the product collection efficiency (USDOE 2005). For example, Radlein (2007) shows that bark yields more biochar than bagasse or wheat straw, but bagasse yields relatively more bio-oil than bark or wheat straw.

Although bio-oil and biochar are generally used to produce energy, biochar used as a soil amendment has been studied intensively. The land application of biochar is not a new concept. Sombroek (2003) shows that in the Amazon Basin, soil has received large amounts

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of charred materials and Erickson (2003) shows that these biochar applications were most likely a result of both the habitation activities and the deliberate soil application by the native populations before the arrival of Europeans. The land application with biochar is positive because biochar has the potential to improve the nutrient retention (Deluca et al. 2009). Deluca et al. present a potential mechanism for how biochar modifies the nutrient transformations. They show that the bio-available C may be adsorbed to the biochar surfaces, thereby reducing the potential for the immobilization of nitrates formed under the biochar stimulation of the nitrification. Thus adding biochar to soil with an organic N source yielded an increase in the net nitrification. Fire also induces a short-term influence on N availability, but biochar may act to maintain this effect for years to decades, Chan et al. (2007) show that if the N fertilizer was not added, the biochar application did not increase the yield of radishes even with 100 t/ha biochar rate. They find that if biochar and the N fertilizer are applied together, the biochar/nitrogen fertilizer interaction is significant and biochar can improve the N fertilizer use efficiency of the plant. Applications of biochar (or similar materials such as the volcanic ash) on the crop yields have been studied since 1980 (Iswaran et al. 1980; Kishimoto and Sugiura 1985; Chidumayo 1994; Glaser et al. 2002; Oguntunde et al. 2004; Steiner et al. 2007). Throughout these studies, there is no consensus on how much biochar should be applied. In these studies, biochar was applied ranging from 0.5 to 135 tons per hectare and most of these applications result in the increase of the crop yields except for Kishimoto and Sugiura (1985) with a 5 and 15 tons per hectare application of the volcanic ash on soybean fields.

METHODOLOGY

This section first illustrates the bio-energy production, the GHG emissions offset and the crops change patterns under the competition among different bio-energy technologies and feedstocks. If biochar produced from pyrolysis is used as a soil amendment, it can help to increase the agricultural production and to reduce the carbon dioxide emission. This section then introduces the benefits from applying biochar in Taiwan. Meanwhile, three conventional econometric models (linear, nonparametric and semi-parametric partial linear regression models) used in the analysis of the relation between benefits and costs of using biochar are explored.

Mathematical programming analysis: modified Taiwan agricultural sector model

The model used herein is based on the price endogenous mathematical programming, which is originally illustrated by Samuelson (1950), who shows that the equilibrium in the perfect competition market can be derived from the optimization model that maximizes the consumer surplus and the producer surplus. McCarl and Spreen (1980) compare the linear programming models used by other planned economic systems to the price endogenous model, and the results showed that the price endogenous model can represent the economic system in a perfectly competitive market. The model is useful in the policy analysis including the soil conservation policy (Chang et al. 1992), the global climate change (Adams et al. 1986; McCarl et al. 1999; Reilly et al. 2002), and the climate change mitigation (McCarl and Schneider 2000). It has also been applied extensively for the research evaluation (Coble et al. 1992; Chang et al. 1991).

Chen and Chang (2005) develop the Taiwan Agricultural Sector Model (TASM) to analyze the Taiwanese agricultural policy in terms of the production and market issues. The TASM is a multi-product partial equilibrium model based on the previous work of Burton and Martin (1987), McCarl and Spreen (1980), Chang et al. (1992), and Coble et al. (1992). This empirical structure has been adapted to Taiwan and used in many policy-related studies such as Chang (2002) and Chen and Chang (2005). The current version of the TASM accommodates more than 110 commodities in 15 sub-regions aggregated into 4 major production and processing regions. We extended the TASM to evaluate the potential economic and the GHG implications of the bio-energy crop production plus the competition with other land uses. The land GHG emissions are also incorporated into the modified TASM. The modified TASM simulates market operations under the assumptions of perfect competition with the individual producers and consumers as price-taker. It also incorporates the price-dependent product demand and the input supply curves.

For this analysis, we add features related to bio-energy into the TASM and construct a modified TASM. The objective function and constraints of the modified TASM are shown as follows:

doi: 10.17221/147/2014 -AGRICECON

$$MAX:U=\sum_i\int\psi(Q_i)dQ_i-\sum_i\int ED(Q_i^M)dQ_i^M-\sum_i\int EXED(TRQ_i)dTRQ_i$$
$$-\sum_i\left[tax\times P^M\times Q_i^M+outtax\times P^M\times TRQ_i\right]+\sum_i\int ES\left(Q_i^X\right)dQ_i^X-\sum_k\int\alpha_k\left(L_k\right)dL_k \quad (1)$$
$$-\sum_k\int\beta_k\left(R_k\right)dR_k-\sum_i\sum_k C_{ik}X_{ik}+\sum_k GP\times AL_k+\sum_i TP_i\times GQ_i$$

Subject to

$$Q_i+Q_i^X+Q_i^G-\sum_k Y_{ik}X_{ik}-(Q_i^M+TRQ_i)\le 0 \quad \text{for all } i \quad (2)$$

$$\sum_i X_{ik}+AL_k+\sum_j EC_{jk}-L_k\le 0 \quad \text{for all } k \quad (3)$$

$$\sum_i f_{ik}X_{ik}-R_k\le 0 \quad \text{for all } k \quad (4)$$

$$\sum_{i,k}E_{gik}X_{ik}-GHG_g\le 0 \quad \text{for all } g \quad (5)$$

Table 1 indicates variables used in the objective function. Equation (1) is our objective function incor-

Table 1. Variables description

Q_i	Domestic demand of i^{th} product
Q_i^G	Government purchases quantity for price supported i^{th} product
Q_i^M	Import quantity of i^{th} product
Q_i^X	Export quantity of i^{th} product
$\psi(Q_i)$	Inverse demand function of i^{th} product
P_i^G	Government purchase price on i^{th} product
C_{ik}	Purchased input cost in k^{th} region for producing i^{th} product
X_{ik}	Land used for i^{th} commodities in k^{th} region
L_k	Land supply in k^{th} region
$\alpha_k(L_k)$	Land inverse supply in k^{th} region
R_k	Labour supply in k^{th} region
$\beta_k(R_k)$	Labour inverse supply in k^{th} region
P^L	Set-aside subsidy
AL_k	Set-aside acreage in k^{th} region
SUB_j	Subsidy on planting j^{th} energy crop
EC_{jk}	Planted acreage of j^{th} energy crop in k^{th} region
$ED(Q_i^M)$	Inverse excess import demand curve for i^{th} product
$ES(Q_i^X)$	Inverse excess export supply curve for i^{th} product
TRQ_i	Import quantity exceeding the quota for i^{th} product
$EXED(TRQ_i)$	Inverse excess demand curve of i^{th} product that the import quantity is exceeding quota.
tax_i	Import tariff for i^{th} product
$outtax_i$	Out-of-quota tariff for i^{th} product
Y_{ik}	Per hectare yield of i^{th} commodity produced in k^{th} region
E_{gik}	g^{th} greenhouse gas emission from i^{th} product in k^{th} region
P_{GHG}	Price of GHG gas
GWP_g	Global warming potential of greenhouse gas
GHG_g	Net greenhouse gas emissions of g^{th}
f_{ik}	Labor required per hectare of commodity i in region k

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porating the domestic and trade policies. Equation (2) is the balance constraint for commodities. Equations (3) and (4) are the resource endowment constraints. Equation (3) controls the cropland and means the agricultural crops, energy crops and the set-aside hectares are competing. Equation (4) is the other resource constraint. Equation (5) is the greenhouse gas balance which shows that the emissions emitted cannot be greater than the total emissions.

Econometric analysis

In the analysis of bio-energy, there are various benefits and costs associated with the procedure of producing and using bio-energy. The main benefits and costs of the biochar application are given as follows.

Benefits:

B_1: Carbon sequestration resulting from biochar;

B_2: Farmers' extra benefits due to increments of the crop output from biochar;

B_3: Reduced irrigation costs in the conventional cropland production (conventional crops mean rice, sugarcane, corn etc, not energy crop itself);

B_4: Reduced costs for the fertilizer use in conventional crops;

B_5: Reduced costs for the seed use in conventional crops.

Costs:

C_1: Production costs for the energy crop production;

C_2: Additional costs for harvesting the energy crop;

C_3: Additional costs for transporting the energy crop to the plant;

C_4: Bio-energy feedstock collection and storage costs;

C_5: Hauling costs for the bio-energy feedstocks where the density of energy crops should play an important role; we may use the following equation to represent their relation;

$$\text{hauling cost} = \frac{38 + 2 \times (0.4714) \times [M/(2.468 \times DEN \times Y)]^{1/2}}{Load\ Size}$$

where Y is the yield per hectare, DEN is the density of the cultivated land for a specific agricultural commodity in the region, M is the feedstock requirement, and the Load Size is 23 tons per truck load. The other constants cover the loading and travel costs.

C_6: Construction costs for the pyrolysis plant (should be affected by inflation, input prices (steel, concrete, etc.), labour supply, and wages);

C_7: Plant operation costs (wage, electricity, and water bills).

Since the most important benefits of producing bio-energy in Taiwan are to increase the environmental benefits (B_1) and to enhance the farmers' revenues (B_2), this study considers the sum of B_1 and B_2, the benefits that the society can eventually obtain related to the biochar used (that is, the net increasing revenue, NIR), as the dependent variables due to their values are estimated in the output. Other benefits and costs, B_3, B_4, B_5 and , are used as independent variables because they are all related to the production and processing activities of energy crop and biochar. This study uses the vector $Z = (X_1, X_2, X_3, X_4, X_5)$ as indexes for the benefits and costs from pyrolysis. X_1 stand for the total nutrient savings including the reduced irrigation costs and the reduced fertilizer cost ($B_3 + B_4$); whereas, X_2 stands for seed savings (B_5). X_3, X_4 and X_5 stand for the additional production costs including the additional seed, energy and labour costs (C_1), the additional costs for harvesting and transporting energy crop to the plant ($C_2 + C_3$) and the biochar application costs including transportation, storage, plant construction and operation costs ($C_4 + C_5 + C_6 + C_7$), respectively. Since our data are collected from two periods, fifteen locations, we use dummies, denoted by $\{P_i\}_{i=1}^{2}$, $\{L_j\}_{j=1}^{15}$ to address these qualitative attributes. As the benefits and costs are estimated based on literatures the environmental conditions of which are not the same as in Taiwan, it is necessary for this study to adjust the values of the variables to reflect the possible boundary where the actual value may locate. Because the irrigation and fertilizer efficiency can be enhanced up to 10%, we assume that the benefits from the nutrient saving (variable X_1) and the reduction of seed use (variable X_2) are adjusted to 8%, 10% and 12% where 10% is the baseline from Lehmann et al. (2006). X_3, X_4 and X_5 represents the associated costs on producing feedstocks that will be used in pyrolysis and the processing costs of biochar. We assume that these costs may increase by 25% due to the inflation and the increasing labour and land costs. This study presents 72 scenarios under the consideration of the nutrient and seed savings, production costs of the energy crop and the biochar application costs.

If the relations between the dependent and independent variables are misspecified, the least squared estimator is biased and inconsistent. As we do not

doi: 10.17221/147/2014 -AGRICECON

know the correct functional form of the independent variables, we use both parametric and nonparametric regression models. In this study, we use three popular models such as the linear regression, the nonparametric kernel regression and the semi-parametric partial linear regression models to analyze how various factors influence the NIR. Based on the estimates of three models, this study employs the one with the minimum mean squared errors to forecast the NIR given some economic conditions. The linear regression takes the form

$$Y = a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_5X_5 + b_1P_1 + + \sum_{j=1}^{14} c_jL_j + \mu \quad (6)$$

where μ stands for the error term. This study used the robust ordinary least squares estimator to estimate the parameters. For preventing from multicollinearity in the estimation, the dummies P_2 and L_{15} are dropped.

On the other hand, the kernel regression model follows the form

$$Y = f(W) + \varepsilon \quad (7)$$

where $W = (X_1, X_2, X_3, X_4, X_5, \{P_i\}_{i=1}^{2}, \{L_j\}_{j=1}^{15})$, f is an unknown and smooth function and ε is the error term. In the nonparametric estimation, this study uses the local linear kernel estimator which is based on the following minimization problem:

$$\min_{\alpha,\beta} \sum_{i=1}^{2} \sum_{j=1}^{15} \left(Y_{ij} - \alpha - (W_{ij} - w)'\beta\right)^2 K\left(\frac{W_{ij} - w}{h}\right) \quad (8)$$

where i and j stand for the period and the location, respectively. h is the bandwidth, which is used as a smoothing parameter and $K(\cdot)$ is the kernel function. The Gaussian kernel function K is selected in our study and the optimal bandwidth is chosen by the least squares cross-validation. The estimator $\hat{\delta} = (\hat{\alpha}, \hat{\beta})'$ can be obtained by

$$\left[\sum_{i=1}^{2} \sum_{j=1}^{15} K\left(\frac{W_{ij} - w}{h}\right) \begin{pmatrix} 1 \\ W_{ij} - w \end{pmatrix} (1, W_{ij} - w)'\right]^{-1} \times \times \sum_{i=1}^{2} \sum_{j=1}^{15} K\left(\frac{W_{ij} - w}{h}\right) \begin{pmatrix} 1 \\ W_{ij} - w \end{pmatrix} Y_{ij}$$

The details of the local liner estimator can be found in Li and Racine (2007). The functional form of the semi-parametric partial linear regression model is given by:

$$Y = b_1P_1 + \sum_{j=1}^{14} c_jL_j + g(Z) + v \quad (9)$$

where $Z = (X_1, X_2, X_3, X_4, X_5)$, g is a smooth function, and v is the error term. The semi-parametric partial linear model uses a combination of the linear regression and the nonparametric regression to estimate the coefficients in the parametric part, denoted by b_1 and $\{c_j\}_{j=1}^{14}$ in Equation (9). The model assumes that the relation between each dummy variable and the dependent variable is linear to separate the qualitative effects from the quantitative effects. The coefficients identify how the period and the location influence the NIR. The nonparametric part of the partial linear model $g(Z)$ is estimated in terms of the local linear kernel estimator and the optimal bandwidth is chosen based on the least squares cross-validation.

RESULTS

Results from mathematical programming

This study examines (1) the Taiwan's bio-energy production and the government subsidy; (2) the cropland occupied by energy crops and the associated GHG emissions offset; (3) the rice field applied with biochar and the increases in the rice supply. In this study, 4 ethanol prices (NT$20, 30, 40, 50 per litre), 3 coal prices (NT$1.7, 3.45, 6 per kg) and 2 GHG prices (NT$ 300 and 500 per ton) are analyzed to examine the questions that the policy makers may be interested in.

The simulation result shows that when Taiwan decides to produce bio-energy, only sweet potato and switchgrass will be the possible energy crops. This is because sweet potato and switchgrass have lower production costs and higher yields. However, when the gas price is high and the ethanol production is expanded, the planted hectares for sweet potato increase and that of switchgrass decrease. When the coal price is high and thus the electricity price is high, more cropland will be converted into the production of switchgrass. Figure 1 and 2 prohibit the planted hectares of sweet potato and switchgrass under various gas and coal prices at the GHG price of NT$300.

Figure 3 presents the net CO_2 emissions reduction from the Taiwan's bio-energy production. The result

doi: 10.17221/147/2014 -AGRICECON

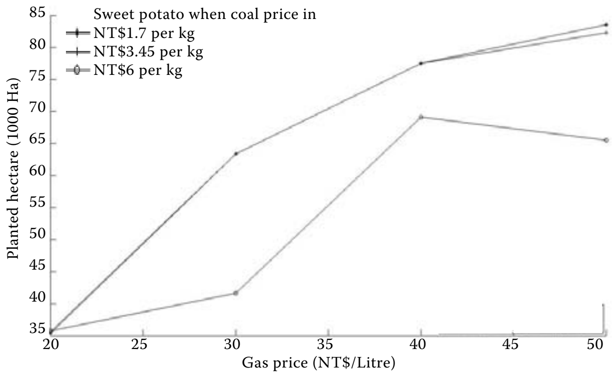

Figure 1. Planted hectares of sweet potato (1000 ha) under various gas and coal prices

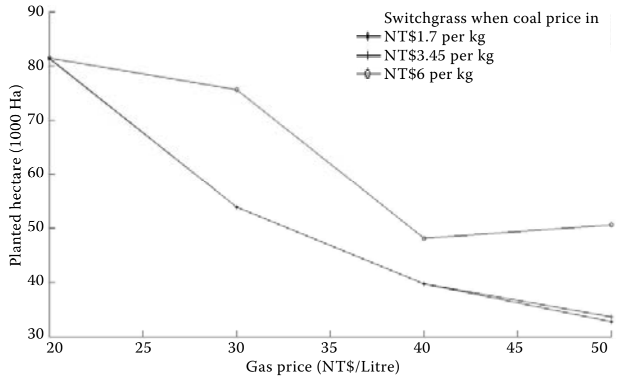

Figure 2. Planted hectares of switchgrass (1000 ha) under various gas and coal prices

indicates that that when the gas price increases, the net CO_2 emissions reduction decreases. This is because when the gas price increases, the production of ethanol increases and, therefore, more cropland land is converted into the production of sweet potato. However, the net CO_2 emissions reduction effect of ethanol is lower than the conventional bioelectricity due to the higher energy conversion rate of bioelectricity and lower hauling costs of feedstocks. When the planted hectares of sweet potato increase, the cropland left for the switchgrass is less and fewer feedstocks can be used for the bioelectricity production, resulting in lower CO_2 emissions reduction from the Taiwan's bio-energy production.

Table 2 summarizes the simulation result under the GHG price of NT$300 and the per hectare subsidy of NT$50 000. The result shows that in general, the production of ethanol and the conventional electricity is negatively related. To subsidize the plantation of energy crops, the Taiwanese government needs to spend, in average, NT$ 5.5 billion dollars annually and both farmers and the whole society benefit

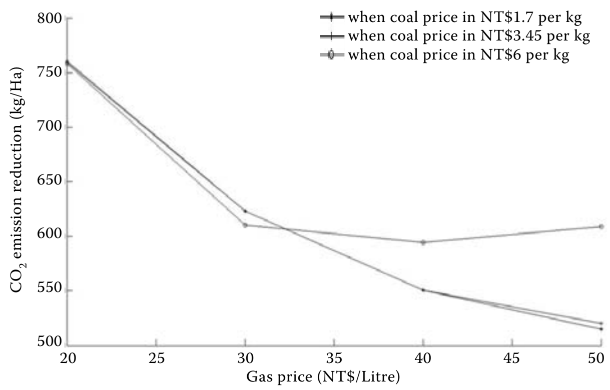

Figure 3. Per hectare CO_2 emissions reduction

from the renewable energy production in terms of the farmers revenue and the social welfare.

When pyrolysis is introduced, biochar can be applied as a soil amendment and increases the crop yields. The pyrolysis-based electricity not only increases the Taiwan's energy security, but it also provides a chance for the farmers to gain. In this study, biochar produced from the fast and slow pyrolysis is examined because the two pyrolysis systems yield a different amount of biochar, and thus the hectares that can be applied with biochar will vary. Table 3 and 4 present the simulation result.

Table 3 shows that the amounts of biochar produced in the fast pyrolysis process are lower than that in the slow pyrolysis process. In average, about 25 500 hectares of rice fields receive biochar as a soil amendment. Interestingly, Chiayi, the county where we assume the pyrolysis plant is built, does not receive biochar for its cropland; instead, biochar is transported to the counties that are further away. This indicates that the benefits in terms of cost savings and yield increases of rice fields in Chiayi are lower than the benefits obtained in Changhua, Pingtung and Ilan. The simulation result shows that when the fast pyrolysis is adopted for the bio-energy and biochar production, about 6300 tons of rice production increase can be achieved.

Table 4 shows that because slow pyrolysis produces more biochar, more rice fields can be applied with biochar and the benefit from the crop yield increase. In addition, we see that most of the counties receiving biochar are located in the Southern and Central Taiwan, where the rice yields are higher, the input costs and transportation costs are lower. Farmers gain more with the application of biochar and the net rice supply can increase up to 38 118 tons annually, depending on the type of pyrolysis adopted.

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Table 2. Summary of the simulation result for GHG price of NT$300

Ethanol Price	NT$/kg	20	30	40	50
Electricity Price	NT$/kg	1.7	1.7	1.7	1.7
Ethanol Production	Million litre	132.7	241.8	219.8	270.7
Electricity Production	Million kwh	277.4	148.0	177.1	111.7
Sweet Potato Planted Acreage (a1)	1000 ha	34.5	72.6	64.4	83.6
Switchgrass Planted Acreage (a2)	1000 ha	81.4	43.5	52	32.8
Sweet Potato Farmers' Revenue (ha)	NT$1000	236.5	274.0	261.6	288.4
Switchgrass Farmers' Revenue (ha)	NT$1000	323.3	323.3	323.3	323.3
Gov. Expenditure on Sweet Potato	Million NT	1 725.4	3 630.5	3 219.5	4 180.5
Gov. Expenditure on Switchgrass	Million NT	3 664.9	1 955.7	2 340.5	1 476.1
CO2 Emission Reduction (b1)	1000 Tons	88.4	66.3	71.6	59.9
Net Social Welfare (c1)	Million NT	23 612.8	34 147.9	44 384	55 005.3
CO2 Emission Reduction (ha) (d1)= (b1)/(a1+a2)	kg/ha	762.3	571.4	614.9	514.8
Net Social Welfare (ha) (e1) = (c1)/(a1+a2)	NT$1000/ha	203.6	294.2	381.3	472.5
Ethanol Price	NT$/kg	20	30	40	50
Electricity Price	NT$/kg	3.45	3.45	3.45	3.45
Ethanol Production	Million litre	132.7	225.5	218.4	267.1
Electricity Production	Million kwh	277.4	172.2	177.1	114.9
Sweet Potato Planted Acreage (a1)	1000 ha	34.5	66.1	64	82.3
Switchgrass Planted Acreage (a2)	1000 ha	81.4	50.6	52	33.7
Sweet Potato Farmers' Revenue (ha)	NT$1000	236.5	271.0	261.6	288.4
Switchgrass Farmers' Revenue (ha)	NT$1000	330.9	330.9	330.9	330.9
Gov. Expenditure on Sweet Potato	Million NT	1 725.4	3 305.5	3 200.9	4 116.7
Gov. Expenditure on Switchgrass	Million NT	3 664.9	2 275.8	2 340.6	1 518.3
CO_2 Emission Reduction (b1)	1000 Tons	88.4	70.9	71.4	60.4
Net Social Welfare (c1)	Million NT	19 742.9	34 962.9	44 664.4	54 994.1
CO2 Emission Reduction (ha) (d1)= (b1)/(a1+a2)	kg/ha	762.3	607.8	615.5	520.2
Net Social Welfare (ha) (e1) = (c1)/(a1+a2)	NT$1000/ha	170.3	299.6	384.9	473.8
Ethanol Price	NT$/kg	20	30	40	50
Electricity Price	NT$/kg	6	6	6	6
Ethanol Production	Million litre	133.1	218.4	210.1	223.3
Electricity Production	Million kwh	277.2	177.7	185.3	172.2
Sweet Potato Planted Acreage (a1)	1000 ha	34.6	63.8	61.6	65.5
Switchgrass Planted Acreage (a2)	1000 ha	81.4	52.2	54.4	50.6
Sweet Potato Farmers' Revenue (ha)	NT$1000	247.4	267.0	261.6	288.4
Switchgrass Farmers' Revenue (ha)	NT$1000	342.0	342.0	342.0	342.0
Gov. Expenditure on Sweet Potato	Million NT	1 729.8	3 191.2	3 080.4	3 276.1
Gov. Expenditure on Switchgrass	Million NT	3 663.2	2 348.5	2 448.2	2 274.8
CO_2 Emission Reduction (b1)	1000 Tons	88.4	71.6	72.6	70.6
Net Social Welfare (c1)	Million NT	25 311.8	35 518.2	45 179.9	55 601.5
CO2 Emission Reduction (ha) (d1)= (b1)/(a1+a2)	kg/ha	762	617	626.2	608.7
Net Social Welfare (ha) (e1) = (c1)/(a1+a2)	NT$1000/ha	218.2	306.2	389.4	479.0

doi: 10.17221/147/2014 -AGRICECON

Table 3. Rice hectares (1000 ha) with biochar application from fast pyrolysis

Pyrolysis	Fast	Total increase of rice (in tons)	Fast	Total increase of rice (in tons)
GHG price	NT$300		NT$500	
Electricity price	NT$1.7		NT$1.7	
Changhua	7.25	1 944.81	7.4	1 985.05
Pingtung	7.49	2 106.19	7.49	2 106.19
Ilan	10.58	2 256.71	10.83	2 310.04
Total	25.32	6 307.71	25.72	6 401.28

Table 4. Rice hectares (1000 ha) with biochar application from slow pyrolysis

Pyrolysis	Slow	Total increase of rice (in tons)	GHG Price	Slow	Total increase of rice (in tons)
GHG Price	NT$300			NT$500	
Electricity Price	NT$1.7		Electricity Price	NT$1.7	
Hsinchu	6.31	1 350.66	Hsinchu	6.31	1 350.66
Miaoli	10.13	2 186.05	Miaoli	12.02	2 593.92
Changhua	23.66	6 346.80	Nantu	3.48	873.13
Yunlin	60.92	15 321.38	Changhua	15.03	4 031.80
Chiayi	28.22	6 349.50	Yunlin	35.98	9 048.97
Kaohsiung	6.91	1 750.99	Chiayi	52.5	11 812.50
Pingtung	7.49	2 106.19	Pingtung	7.49	2 106.19
Ilan	12.69	2 706.78	Ilan	12.47	2 659.85
Total	156.33	38 118.34	Total	145.29	34 477.01

Results from econometric analysis

This section provides the estimation of the NIR of rice and the goodness-of-fit measure of the estimation in terms of the mean squared error (MSE) for the linear regression, the kernel regression and the semi-parametric partial linear regression models. The kernel regression model dominates the others in terms of the MSE, so that the kernel estimator is chosen for the NIR forecasting.

The simulation to forecast the NIR of rice after using bio-energy is conducted. The experiment is concerned with the forecasts of the NIR of rice in different scenarios, where the possible changes could occur to benefits and costs of using bio-energy.

Model comparison

In order to determine the optimal model for further forecasting of the NIR, this study estimates the NIR of rice in terms of the linear regression, the kernel regression and the semi-parametric partial linear regression models. As there are up to seventeen dummy variables (two periods and fifteen locations) considered in the kernel regression model and fifteen dummy variables (one period and fourteen locations) considered in the linear regression and semi-parametric partial linear regression models, there may exist some dummy variables which are irrelevant to the dependent variable. Therefore, our study tests the significance of each dummy variable and retains those significant dummies in the goodness-of-fit analysis and in forecasting the NIR.

From (6) and (9), it can be observed that the functional form of dummy variables in the linear regression and the semi-parametric partial linear regression models is linear. Therefore, the criterion used to verify the significance of dummy variables in these two models is the conventional Student's t-test. On the other hand, the functional form of dummy variables in the kernel regression model in (7) is assumed to an unknown function such that the Student's t-test is not appropriate in this case. Racine et al. (2006) propose a consistent test of significance of an explanatory variable in a non-parametric regression setting that is analogous to a simple t-test in a parametric regression setting. The null hypothesis of their test can be written as

$$H_0: E(y|x, k) = E(y|x) \text{ almost everywhere} \quad (10)$$

doi: 10.17221/147/2014 -AGRICECON

where k is the regressor that is irrelevant. In our study, k includes $\{P_i\}_{i=1}^{2}$. $\{L_j\}_{j=1}^{15}$

After ignoring the insignificant dummy variables, the functional forms of the linear regression, the kernel regression and the semi-parametric partial linear regression models used in the goodness-of-fit analysis can be given by:

$$Y = a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_5X_5 + b_1P_1 + + c_7L_7 + c_9L_9 + c_{10}L_{10} + \mu \quad (11)$$

$$Y = f(X_1, X_2, X_3, X_4, X_5, P_1, L_8, L_{10}, L_{12}, L_{13}) + \varepsilon \quad (12)$$

$$Y = b_1P_1 + c_5L_5 + c_{10}L_{10} + c_{12}L_{12} + c_{13}L_{13} + + g(Z) + v \quad (13)$$

To evaluate the performance of models, this study computes the MSE of all models on the estimation of the NIR based on (11), (12) and (13). The results are reported in Table 5. It can be observed that the kernel estimator apparently outperforms the others in the sense of the MSE. Therefore, it convinces us that the kernel regression is optimal among the three models for the forecasting analysis in this study.

Table 5. Mean squared error (MSE) of NIR estimation.

Linear	Kernel	Partial Linear
80.92386	13.77382	60.2697

NIR forecasting

Figure 4 shows the forecasted NIR in terms of (12). The maximum NIR can achieve up to NT$ 419 400, which occurs in the case of the efficient nutrient savings and seed savings, and high production costs for the energy crop and for biochar (i.e. $1.2X_1$, $1.2X_2$, 1.25 X_3, $1.25X_5$). Farmers can get a higher NIR if they could improve the nutrient savings (i.e. $1.2X_1$), keeping other criteria fixed. Similarly, the benefits go up if the farmers could improve the seed savings (i.e. $1.2X_2$) , keeping other criteria fixed. The benefits are relatively high when the harvesting and transporting costs for the energy crop and the processing and hauling cost of biochar are low (i.e. X_4 , X_5). In others words, if other criteria are fixed (i.e. X_1 , X_2 , X_3 are fixed), the NIR is higher if the farmers could lower the harvesting and transporting costs for the energy crop and the processing and hauling cost of biochar. We observe that the efficient nutrient saving ($1.2X_1$) plays the most important role in enhancing the NIR (NIR from scenario 49 to 72 is relative higher than the others). This result indicates that the farmers should give priority to the improvement of the nutrient saving to make a higher NIR. Second, the farmers could improve the NIR if seed use is more efficient ($1.2X_2$).

CONCLUSION

Taiwan is interested in producing energy domestically and one option is to utilize the set-aside land to produce the bio-energy feedstocks. This paper examines that if pyrolysis is adopted and when biochar is used as a soil amendment, it is possible to increase both the supply of bio-energy and food. The development of the pyrolysis-based bio-energy in Taiwan does reduce the net GHG emissions, but it only has a small contribution in terms of the global climate shift. The farmers' income can be increased, but the government subsidy for the development of this industry may be significant. However, from the energy security point of view, the investment from the government may be needed since the development of bio-energy reduces the reliance on the foreign energy sources. The results indicate that the biochar utilization can potentially increase the farmers' income if rice is planted and the net increasing revenues per hectare can be achieved up to NT$ 419 400. Moreover, we find that the farmers should give priority to the improvement of the nutrient saving to make higher benefits. Second, the farmers could improve the NIR if the seed use is efficient and the harvesting and transporting costs for the energy crop and the processing

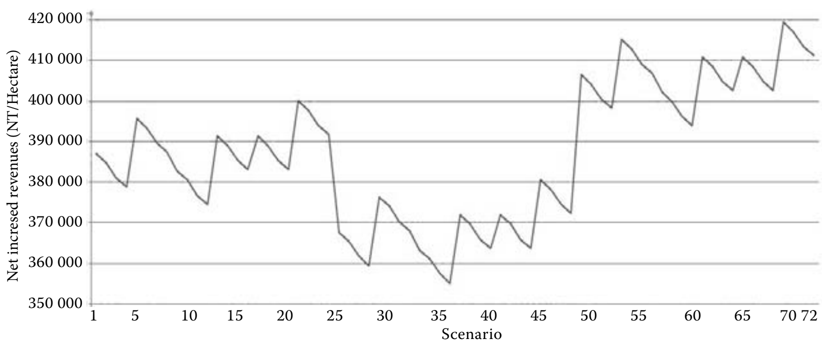

Figure 4. Forecasted NIR from rice plantation

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and hauling cost of biochar are lower. However, the results would vary if the pyrolysis plant is chosen in other locations since the hauling distance will be changed. Therefore, the amounts of biochar that the counties will receive will be different and therefore, the onsite biochar benefits (and hence the farmers net increasing revenues) will change.

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Appendix

	X_3, X_4, X_5	$X_3, X_4, 1.25X_5$	$X_3, 1.25X_4, X_5$	$X_3, 1.25X_4, 1.25X_5$	$1.25X_3, X_4, X_5$	$1.25X_3, X_4, 1.25X_5$	$1.25X_3, 1.25X_4, X_5$	$1.25X_3, 1.25X_4, 1.25X_5$
X_1, X_2	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$X_1, 0.8X_2$	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
$X_1, 1.2X_2$	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
$0.8X_1, X_2$	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)
$0.8X_1, 0.8X_2$	(33)	(34)	(35)	(36)	(37)	(38)	(39)	(40)
$0.8X_1, 1.2X_2$	(41)	(42)	(43)	(44)	(45)	(46)	(47)	(48)
$1.2X_1, X_2$	(49)	(50)	(51)	(52)	(53)	(54)	(55)	(56)
$1.2X_1, 0.8X_2$	(57)	(58)	(59)	(60)	(61)	(62)	(63)	(64)
$1.2X_1, 1.2X_2$	(65)	(66)	(67)	(68)	(69)	(70)	(71)	(72)

The first column and the first row identify the condition in each scenario

The value in the parenthesis stand for the scenario corresponding to the specific condition

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