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A dynamic framework of sustainable development in agriculture and bioenergy

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Abstract: The use of fossil fuels raises serious environmental concerns and causes major adverse effects such as the ocean level rise and the increased occurrence of hurricanes. To alleviate such problems, a global movement towards the generation of renewable energy is considered to be an effective way to help reducing the global greenhouse gas emissions and to sustain social development. Bioenergy is one attractive renewable energy source in Taiwan because a substantial amount of cropland has been released after the participation in the World Trade Organization (WTO). This study proposes two dynamic agricultural sector models to analyse how changes in the land fertility affect agricultural activities and bioenergy development. The analytical result indicates that economic incentives such as the direct subsidy and tax credit can be used to maintain a desired fertility level. In addition, the objectives of bioenergy development must be defined in advance because changes in discount rates and planning horizons have considerable influences on the effectiveness of policies.

Keywords: agricultural activities, bioenergy, dynamic programming, intergenerational equity

Anthropogenic emissions are considered to be the main cause of the climate change, which has become an important issue to many countries because it can and eventually will result in severe and irreversible harm to human society (IPCC 2007). For example, the United States of America (USA) and Canada just experienced unprecedented ice storms in early 2015, while India encountered catastrophic heat waves during the summer. Sea level rise induced by the melting glaciers is another consequence that should not be ignored because many countries are likely to experience the coastal erosion or even a complete inundation of their landmass within a few decades. In addition, changes in the regional temperature and precipitation can directly influence agricultural activities and cause an unstable world food supply. Each of these consequences is potentially slowing down economic growth and putting additional constraints on social development. Therefore, it is necessary to find effective methods to mitigate the climate change and to ensure that the benefits obtained by the future generations will not be decreased.

Bioenergy is an attractive energy source to Taiwan where a substantial amount of cropland is released, creating a potential land source for the energy crop production. Domestically produced energy can enhance Taiwan's energy security (Chen et al. 2011; Welfle et al. 2014) and prevent it from strong climate change consequences, such as the rising sea levels and an increase in the incidence of tropical cyclones (IPCC 2007). Early studies have shown that bioenergy can increase Taiwan's welfare in terms of the increased energy supply and the reduction of the greenhouse gas (GHG) emissions (Chen et al. 2011; Kung et al. 2014), but they do not incorporate the farmers' responses in later planning periods, limiting the usefulness of information about the long-term planning of the bioenergy development provided to the policy makers (McCarl and Schneider 2003).

Intensive cultivation reduces the land fertility (Dubois 2002; Olesen and Bindi 2002), which may not be observable in the short run but does impact on the social welfare. In addition, because bioenergy is produced by agricultural materials, the constant

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supply of feedstocks plays a significant role in the bioenergy development. Several studies have shown that economic benefits and environmental maintenance may be achieved through the utilization of bioenergy (McCarl and Schneider 2000; Gaunt and Lehmann 2008; Chen et al. 2011), but they do not indicate how the intensity of land use affects the bioenergy production and emission mitigation in the long run.

The objective of this study is to formulate two agricultural sector models under different dynamic situations. The first model illustrates that during the long-run development of bioenergy, the government maximises the social welfare by imposing various agricultural policies. The second model incorporates the intergenerational fairness by considering the gain and loss simultaneously. Both models specify the regional agricultural activities, land use, bioenergy production, and the GHG emission effects. This study contributes by providing analytical approaches for the long-term planning, and by accommodating the impact of the change in land fertility on agricultural activities and the bioenergy production, all of which could assist the governors in establishing sustainable agricultural and bioenergy policies.

LITERATURE REVIEW ON AGRICULTURAL AND BIOENERGY STUDIES

The global climate shift, caused by the intensive use of non-renewable fossil fuels, is an important concern in the modern society (IPCC 2007). Replacing fossil fuels with low-carbon fuel alternatives is important to improve the energy security and to mitigate the climate change (Fargione et al. 2008).

Bioenergy is one alternative that meets such requirements, and it has been widely produced for decades. However, the deforestation and a sudden major shift in land use must be avoided during the bioenergy production to achieve the climate change mitigation (Fargione et al. 2008; Searchinger et al. 2008; Djomo et al. 2015; Gustavsson et al. 2015). Wang (2007) points out that the ethanol production may eventually result in higher GHG emissions and Fargione et al. (2008) indicate that whether biofuel is a low-carbon energy source or not depends on how it is produced. Field and Campbell (2008) show that the net influence on the climate may be either cooling or warming, depending on the choice of the bioenergy technology. One bioenergy technology called pyrolysis is to decompose organic materials and to convert biomass into the bio-oil, bio-gas and bio char (Czernik and Bridgwater 2004; Bridgwater 2005). Lehmann et al. (2006) show that the net COR_2R offset can be 12–84% greater if the bio char is used as a soil amendment, while McCarl et al. (2009) point out that the pyrolysis can have offset efficiencies greater than 100% when compared with the emissions of the fossil fuel inputs that are replaced. In addition, Kung et al. (2015) indicate that the long-run stability of feedstock supply must be taken into account to reduce the production costs and to improve the environmental quality.

Land fertility plays a significant role in the bioenergy development over the long run because the overuse of land now will decrease commodity outputs in the later planning periods (Havlin et al. 1999; Moran et al. 2000; Steiner et al. 2007), and some incentives are needed so that farmers are willing to rotate their land (Dubois 2002; Ridier et al. 2016). Moreover, improper agricultural practices may provide benefits in the short run, but the welfare will be sacrificed in the long run (Olesen and Bindi 2002). The study proposes two agricultural sector models by incorporating the land fertility to analyse the potential optimal solutions under different considerations in the long-run bioenergy development.

MODEL FORMULATION

Samuelson (1950) shows that an optimisation model that maximises the sum of the producer surplus and consumer surplus can result in equilibrium in the perfect competition market. Based on this concept, Takayama and Judge (1971) establish a mathematical programming model with spatial distribution properties, while Duloy and Norton (1973) apply this idea to analyse the Mexican agricultural sectors. This modelling framework is found to be useful in the policy analysis because it can represent the economic system in a perfectively competitive market (McCarl and Spreen 1980). It has become a popular tool in the environmental and resource analysis including biofuels, ozone, acid rain, soil conservation policy, climate change, and climate change mitigation (Tyner 1979; Hamilton et al. 1985; Adams et al. 1986, 1999; Chang et al. 1992; McCarl and Schneider 2000), and in the research and policy evaluation (Burton and Martin 1987; Chang et al. 1992; Coble et al. 1992; Chen and Chang 2005).

The mathematical programming model has been utilized in the study of agricultural problems. McCarl and Spreen (1980) develop a price endogenous, partial equilibrium model to investigate agricultural policies

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and their efficiency in the allocation of agricultural resources. Chen et al. (2011) extend this framework to analyse the changes on social welfare due to the bioenergy production. Field and Campbell (2008) look for the potential resources that can be used for the large-scale bioenergy production, while Kung et al. (2015) investigate the efficient resource allocation under the multiple bioenergy alternatives. This study proposes two alternative agricultural sector models to discuss the factors that have potential significant influences on the bioenergy development in the long-term decision-making.

Basic agricultural sector model formulation

Equilibrium in domestic agricultural markets can be achieved by maximizing the sum of the consumer surplus and producer surplus for every commodity. If *i* commodities are produced in *k* regions through production activities $XR_{ik}R$, the total production of commodity *i*, denoted as QR_iR, is obtained by multiplying the per hectare yields ($YR_{ik}R$) by hectares cultivated ($XR_{ik}R$). By assuming all commodities are sold in the wholesale markets with an average price of P_i^Q, the inverse demand functions can be expressed as below:

$$P_i^Q = \varphi\left(Q_i\right) \qquad \forall i \tag{1}$$

Assume $XR_{ik}R$ requires both regional inputs (i.e. land) and purchased inputs (i.e. fertilizer). For regional inputs, their prices are endogenously determined by the derived demand and regional supply functions, but the prices of the purchased inputs are determined exogenously. Therefore, the regional input supply functions can be expressed as follows:

$$P_k^L = \alpha_k\left(L_k\right) \quad \forall k \tag{2a}$$

$$P_k^R = \beta_k\left(R_k\right) \quad \forall k \tag{2b}$$

where P_k^L, P_k^R, L_k, R_k are the land rent, the user prices of other resources, the quantity of land, and resource supply, respectively.

With such assumptions, the basic form of agricultural sector model can be presented as follows:

$$\text{Max} \sum_i \int \varphi\left(Q_i\right) dQ_i - \sum_i \sum_k C_{ik} X_{ik} - \\ - \sum_k \int \alpha_k\left(L_k\right) dL_k - \sum_k \int \beta_k\left(R_k\right) dR_k \tag{3}$$

Subject to:

$$Q_i - \sum_k Y_{ik} X_{ik} \le 0 \quad \forall i \tag{4}$$

$$\sum_i X_{ik} - L_k \le 0 \quad \forall k \tag{5}$$

$$\sum_i f_{ik} X_{ik} - R_k \le 0 \quad \forall k \tag{6}$$

where C_{ik} is the purchased input cost, Y_{ik} is the commodity yield, and f_{ik} is the labour required.

Government intervention usually involves in the social planning and Figure 1 shows the welfare effects. The government intervenes by purchasing a commodity at a higher price ($P^g > P^*$), and as a result, the original demand curve *DD'* is kinked to *DD"* and the new equilibrium moves from *E* to *E'*. Therefore, the influences on the market equilibrium should be incorporated into the welfare analysis to reflect the policy changes.

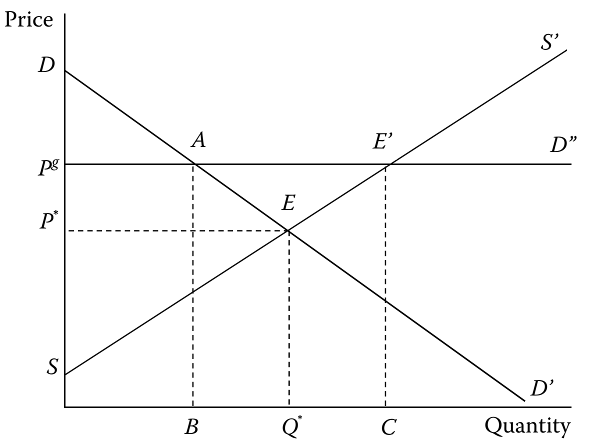

Figure 1. Welfare effect from the government purchase program

the original demand for the commodity is *DD'* (without government intervention); the equilibrium is at point *E*. The government intervenes in the market by purchasing this commodity at a higher price ($P^g > P^*$). As a result the demand curve is kinked to *DD"*, and the new equilibrium occurs at *E'*. Under the government purchase policy, the total supply increase to OH where OG is consumed by the society and GH is purchased by the government. Therefore, the objective function changes to *SDE* + *EE'F* from *SDE* and *SDE* + *EE'F* is calculated by OGFD + GHE'F OSE'H. This is why the government expenditure is added to the objective function

Source: by the author, Chih-Chun Kung, based on the theory of welfare economics

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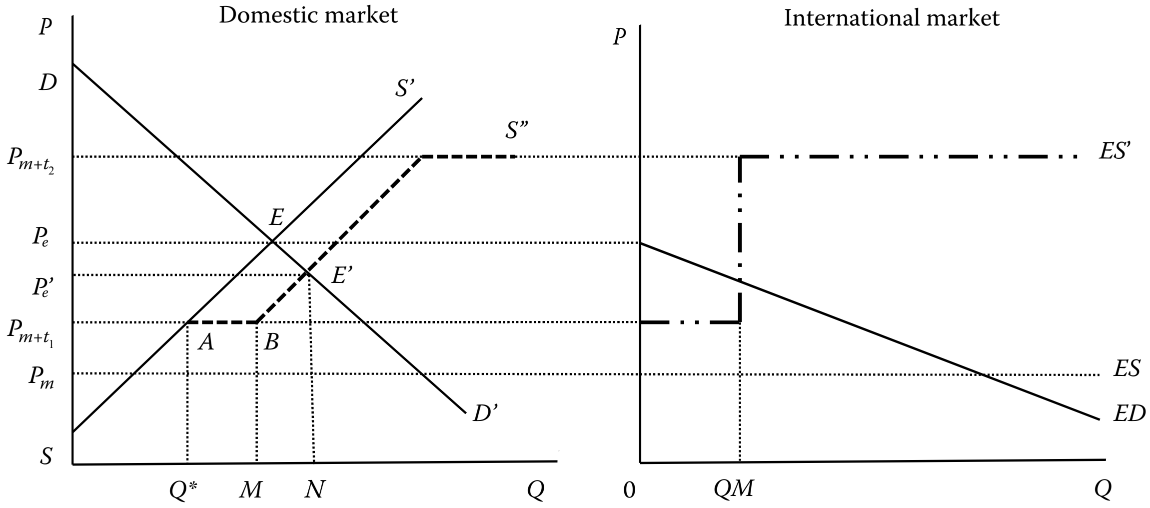

Figure 2. Welfare effect from the import and export

the import and export effects for a small and closed economy where *SS*' and *DD*' determine the domestic equilibrium price (P_e). In an open economy, the international commodity price (P_m) is determined by the domestic excess demand and excess supply from other countries. With tariffs t_1 and t_2 where $t_2 > t_1$, the new equilibrium goes to *E*' and consequently the welfare will increase by the area of *AEE'B*, which portrays the tax effect on domestic commodity production

Source: by the author, Chih-Chun Kung, based on the theory of welfare economics

Import and export effects may also be considered. Figure 2 shows that in a small and closed economy, *SS*' and *DD*' determine the domestic equilibrium price (P_e). In an open economy, the international commodity price (P_m) is determined by the domestic excess demand and the excess supply from other countries. With tariffs t_1 and t_2, where $t_2 > t_1$, the new equilibrium goes to *E*' and thus the welfare will increase the area of *AEE'B*. Emission trade can also be accommodated to explore the consequences of the mitigation strategies.

However, a partial equilibrium model cannot incorporate the changes of the land use and agricultural sectors outside Taiwan. Moreover, the model assumes that the supply and prices of foreign commodities are exogenous. Thus, this framework may not be useful for a large country such as the USA or Brazil, whose agricultural production has a considerable influence on the global market.

Model I: Agricultural sector model with sequential decisions

Farmers perceive the current equilibrium price and make decisions for the next year, implying that the agricultural activities and the availability of bioenergy feedstocks can be altered. Therefore, a sequential analysis may be employed in the long-term planning (Martins and Marques 2007).

The study proposes a modified agricultural sector model to deal with such dynamic situations. The model coefficients are functionally dependent upon the earlier model solutions and an exogenously speci-

$$\text{Max } V_t = \sum_i \int \psi(Q_{it}) dQ_{it} - \sum_k \int \alpha_{kt}(L_{kt}) dL_{kt} - \sum_k \int \beta_{kt}(R_{kt}) dR_{kt} - \sum_i \sum_k C_{ikt} X_{ikt} + \sum_i \int ED(Q_{it}^M) dQ_{it}^M +$$
$$+ \sum_i \int EXED(TRQ_{it}) dTRQ_{it} - \sum_i \int ES(Q_{it}^X) dQ_{it}^X + \sum_i \left[tax_{it} \times Q_{it}^M + outtax_{it} \times TRQ_{it} \right] +$$
$$+ \sum_i P_{it}^G \times Q_{it}^G + \sum_k P^L \times AL_{kt} - P_{GHGt} \times \sum_g GWP_{gt} \times GHG_{gt} \quad (7)$$

Subject to:

$$Q_{it} + Q_{it}^X + Q_{it}^G - \sum_k Y_{ikt} X_{ikt} - \left(Q_{it}^M + TRQ_{it} \right) \le 0 \qquad \forall i,t \quad (8)$$

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fied time path. This model is to optimize the social welfare for each time period instead of solving over all time periods simultaneously. There is no guarantee that these solutions are optimal over all periods. Rather, the solution represents an adaptive stream of decisions (Yang et al. 2002). The objective function is then reformatted (Equation 7).

$$\sum_i X_{ikt} + AL_{kt} - L_{kt} \leq 0 \quad \forall k,t \tag{9}$$

$$\sum_i f_{ikt} X_{ikt} - R_{kt} \leq 0 \quad \forall\, k,t \tag{10}$$

$$\sum_{i,k} E_{gikt} X_{ikt} - GHG_{gt} \leq 0 \qquad \forall g,t \tag{11}$$

where $P^{Q}_{it+1} = \psi(Q_{it})$, subscripts i, k, g, t represent i^{th} product, k^{th} region, g^{th} GHG, and t^{th} period, respectively.

Q_{it} – domestic demand
Q^G_{it} – government purchases quantity with supporting program
Q^M_{it} – import quantity
Q^X_{it} – export quantity
Q^R_{it} – quantity of agricultural wastes collected
$\psi(Q_{it})$ – inverse demand function
P^G_{it} – government purchase price
C_{ikt} – purchased input cost
C^R_{ikt} – collected and transported costs
X_{ikt} – land use
L_{kt} – land supply
$\alpha_{kt}(L_{kt})$ – land inverse supply
R_{kt} – resource supply
$\beta_{kt}(R_{kt})$ – resource inverse supply
P^L – set-aside subsidy
AL_{kt} – set-aside acreage
$ED(Q^M_i)$ – inverse excess import demand curve
$ES(Q^X_i)$ – inverse excess export supply curve
TRQ_i – import quantity exceeding the quota
$EXED(TRQ_i)$ – inverse excess demand curve that the import quantity is exceeding quota.
tax_i – import tariff
$outtax_i$ – out-of-quota tariff
Y_{ik} – per hectare yield
P_{GHG} – price of GHG gas
GWP_g – global warming potential
GHG_g – net greenhouse gas emissions
fR_{ik} – labour required per hectare

Equation 7 is the objective function specifying the domestic and international trade policies. The GHG emission is included to reflect the loss of welfare from higher emissions. Equation 8 represents a balance constraint by showing that the quantity of commodity sold is less than produced. Equations 9 and 10 control the cropland and other resource constraints, while Equation 11 is the GHG balance constraint. The optimal conditions for each period of this sequential model can then be analysed through a setting of the Lagrangian and Kuhn-Tucker conditions (Equation 12).

The optimal production in every period t is shown as Equations 13 to 14.

$$\frac{\partial L}{\partial X_{ikt}} = -C_{ikt} + \delta_{it} Y_{ikt} \tag{13}$$

$$\frac{\partial L}{\partial X_{ikt}} X_{ikt} = 0 \tag{14}$$

$$X_{ikt} \geq 0 \tag{15}$$

$$\begin{aligned} L = & \int \psi(Q_{it}) dQ_{it} - \sum_k \int \alpha_{kt}(L_{kt}) dL_{kt} - \sum_k \int \beta_{kt}(R_{kt}) dR_{kt} - \sum_i \sum_k C_{ikt} X_{ikt} + \sum_i \int ED(Q^M_{it}) dQ^M_{it} + \\ & + \sum_i \int EXED(TRQ_{it}) dTRQ_{it} - \sum_i \int ES(Q^X_{it}) dQ^X_{it} + \sum_i \left[tax_{it} \times Q^M_{it} + outtax_{it} \times TRQ_{it} \right] + \\ & + \sum_i P^G_{it} \times Q^G_{it} + \sum_k P^L \times AL_{kt} - P_{GHGt} \times \sum_g GWP_{gt} \times GHG_{gt} - \\ & - \delta_{it} \left(Q_{it} + Q^X_{it} + Q^G_{it} - \sum_k Y_{ikt} X_{ikt} - \left(Q^M_{it} + TRQ_{it} \right) \right) - \pi_{it} \left(\sum_i X_{ikt} + AL_{kt} - L_{kt} \right) - \\ & - \gamma_{it} \left(\sum_i f_{ikt} X_{ikt} - R_{kt} \right) - \varepsilon_{gt} \left(\sum_{i,k} E_{gikt} X_{ikt} - GHG_{gt} \right) \end{aligned} \tag{12}$$

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Equation 13 shows that in every period, the input cost is equal to the product of productivity and the commodity price. Equation 14 ensures that the agricultural activity can result in a positive value if the land is cultivated or that it will be valued at zero if no activity has been carried out. Equation 15 shows that agricultural activities must be nonnegative.

$$\frac{\partial L}{\partial Q_{it}} = \varphi(Q_{it}) - \delta_{it} \le 0 \quad (16)$$

$$\frac{\partial L}{\partial Q_{it}} Q_{it} = \left[\varphi(Q_{it}) - \delta_{it}\right] Q_{it} = 0 \quad (17)$$

$$Q_{it} \ge 0 \quad (18)$$

The optimal condition of consumption in every period can also be accessed. Equation 16 shows that for every period, people keep consuming commodities until the producer's willingness to accept is greater than or equal to the consumer's willingness to pay. Equation 17 is the complementary slackness condition, representing that the commodity is valued at zero if it is not totally consumed or that it has a nonzero value if the commodity is totally consumed. Equation 18 ensures that the consumption in any period must be nonnegative.

$$\frac{\partial L}{\partial L_{kt}} = -\alpha_{kt}(L_{kt}) + \pi_{it} \le 0 \quad (19)$$

$$\frac{\partial L}{\partial L_{kt}} L_{kt} = \left[-\alpha_{kt}(L_{kt}) + \pi_{it}\right] L_{kt} = 0 \quad (20)$$

$$L_{kt} \ge 0 \quad (21)$$

Equation 19 is the condition of the optimal land use, which shows that in the equilibrium of any period, the cost of using land is greater than or equal to the cost of the land supply. Equation 20 shows that the land will have a nonzero value only if it is fully utilized. Equation 21 indicates that the land area engaged in agricultural activities must be nonnegative.

$$\frac{\partial L}{\partial R_{kt}} = -\beta_{kt}(R_{kt}) + \gamma_{it} \le 0 \quad (22)$$

$$\frac{\partial L}{\partial R_{kt}} R_{kt} = \left[-\beta_{kt}(R_{kt}) + \gamma_{it}\right] R_{kt} = 0 \quad (23)$$

$$R_{kt} \ge 0 \quad (24)$$

Equation 22 is the condition of the optimal resource use. It shows that the cost of using resources is greater than or equal to the resource price. Equation 23 ensures that the resource has a nonzero value only if it is fully utilized. Equation 24 shows that the amount of resources utilized in production must be nonnegative.

$$\frac{\partial L}{\partial \delta_{it}} \delta_{it} = \left\{Q_{it} + Q_{it}^X + Q_{it}^G - \sum_k Y_{ikt} X_{ikt} - \right.$$
$$\left. -\left(Q_{it}^M + TRQ_{it}\right)\right\} \delta_{it} = 0 \ ; \ \forall i \quad (25)$$

$$\delta_{it} \ge 0 \quad (26)$$

Equation 25 shows that the commodity price is of a nonzero value if production activity is fully engaged; otherwise, it is zero. Equation 26 ensures that the commodity must be nonnegative.

$$\frac{\partial L}{\partial \pi_{it}} \pi_{it} = \left(\sum_i X_{ikt} + AL_{kt} - L_{kt}\right) \pi_{it} = 0 \ ; \ \forall k \quad (27)$$

$$\pi_{it} \ge 0 \quad (28)$$

$$\frac{\partial L}{\partial \gamma_{it}} \gamma_{it} = \left(\sum_i f_{ikt} X_{ikt} - R_{kt}\right) \gamma_{it} = 0 \ ; \ \forall k \quad (29)$$

$$\gamma_{it} \ge 0 \quad (30)$$

The complementary slackness conditions of the optimal land and resource prices in every period can be expressed as Equations 27 and 29, respectively. Equations 28 and 30 ensure that their prices must be nonnegative.

With the positive production activity, consumptions, and endogenously determined commodity prices, we obtain Equations 31 and 32.

$$\varphi(Q_{it}) = \delta_{it} \quad (31)$$

$$C_{ikt} = \delta_{it} Y_{ikt} \quad (32)$$

By plugging Equation 31 into Equation 32, we get

$$C_{ikt} = \varphi(Q_{it}) Y_{ikt} \quad (33)$$

Equation 33 shows that the revenue from one unit of production should equal the input costs in every period. That is, to determine the optimal production activity that maximizes welfare, the condition of the marginal revenue being equal to the marginal cost must hold in every period. The same logic is applied to the land and resources, and we obtain Equations 34 and 35.

$$\alpha_{kt}(L_{kt}) = \pi_{it} \quad (34)$$

$$\beta_{kt}(R_{kt}) = \gamma_{it} \quad (35)$$

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$$\text{Max} f = \sum_{t=0}^{T} f\left\{Q(t),\ X(t),\ Y(t), C(t), L(t),\ R(t),\ AL(t),\ TRQ(t), t\right\} \tag{36}$$

$$\begin{aligned} f = &\sum_{i,t}(1+\rho)^{-t} \times \Big\{ \int \psi(Q_{it})\,dQ_{it} - \sum_{k,t}\int \alpha_{kt}(L_{kt})\,dL_{kt} - \sum_{k,t}\int \beta_{kt}(R_{kt})\,dR_{kt} - \\ &-\sum_{i,t}\sum_{k} C_{ikt}X_{ikt} + \sum_{i,t}\int ED(Q_{it}^{M})\,dQ_{it}^{M} + \sum_{i,t}\int EXED(TRQ_{it})\,dTRQ_{it} - \\ &-\sum_{i,t}\int ES(Q_{it}^{X})\,dQ_{it}^{X} + \sum_{i,t}\left[tax_{it}\times Q_{it}^{M} + outtax_{it}\times TRQ_{it}\right] + \\ &+\sum_{i,t} P_{it}^{G}\times Q_{it}^{G} + \sum_{k,t} P^{L}\times AL_{kt} - P_{GHGt}\times \sum_{g,t} GWP_{gt}\times GHG_{gt} \Big\} \end{aligned} \tag{37}$$

Subject to:

$$Q_{it} + Q_{it}^{X} + Q_{it}^{G} - \sum_{k} Y_{ikt}X_{ikt} - \left(Q_{it}^{M} + TRQ_{it}\right) \le 0 \quad \forall i,t \tag{38}$$

Model II: Agricultural sector model with intertemporal fairness

Sustainable development in agriculture is an important issue. Intensive production activities provide benefits in the short run, but deficits may occur in the long run. That is, the benefits obtained from current intensive land use are merely a "pre-consumption" of future benefits. Therefore, current practice without consideration of land rotation and fertility may result in an unsustainable pattern in agricultural systems, and eventually hamper the development of bioenergy. The second proposed model incorporates the characteristic of intergenerational equity to analyse factors that must be considered in long-term planning of bioenergy development.

The objective function f of the second model is expressed as Equation 36. Equation 36 can be extended to the form of Equation 37.

$$\sum_{i} X_{ikt} + AL_{kt} - L_{kt} \le 0\ ;\ \forall k,t \tag{39}$$

$$\sum_{i} f_{ikt}X_{ikt} - R_{kt} \le 0\ ;\ \forall k,t \tag{40}$$

$$\sum_{i,k} E_{gikt}X_{ikt} - GHG_{gt} \le 0\ ;\ \forall g,t \tag{41}$$

$$\begin{aligned}\theta_{k,t+1} - \theta_{k,t} = &-\mu\left(\sum_{i} X_{ikt}/L_{kt}\right) + \\ &+\sigma\left(L_{kt} - \sum_{i} X_{ikt}\right)/L_{kt} \quad \forall k,t\end{aligned} \tag{42}$$

$$\theta_{k,0} = \theta_{k,T+1} = \tau \tag{43}$$

New variables are defined as below:

θ_{kt} – land fertility of region k in period t
μ – rate of fertility loss under cultivation
σ – rate of fertility recovery for idle land
T – current condition of land fertility
ρ – assumed constant discount rate in every period

Equation 37 maximizes the welfare of all periods simultaneously. Equations 38–41 are the supply and demand balance constraints. Equation 42 is the state equation which depicts that the weighted change of aggregate land fertility is related to aggregate agricultural activities at rate μ and σ. Equation 43 defines the initial and terminal conditional conditions by assuming that agricultural activities engaged by the future generations can be cultivated with the same land fertility.

$$\begin{aligned} L = &H_t\left(Q_t, X_t, Y_t, C_t, L_t, R_t, AL_t, TRQ_t, \theta_t, \gamma_t, \delta_t, \varphi_t, \varepsilon_t, \rho_t, \tau\right) + \sum_{k}\lambda_{kt}(\text{state equations}) + \sum_{i}\varphi_{it}(\text{constraints}) \\ &= (1+\rho)^{-t}\Big\{\int\psi(Q_{it})\,dQ_{it} - \sum_{k}\int\alpha_{kt}(L_{kt})\,dL_{kt} - \sum_{k}\int\beta_{kt}(R_{kt})\,dR_{kt} - \sum_{i}\sum_{k}C_{ikt}X_{ikt} + \sum_{i}\int ED(Q_{it}^{M})\,dQ_{it}^{M} + \\ &+\sum_{i}\int ES(Q_{it}^{X})\,dQ_{it}^{X} + \sum_{i}\int ED(Q_{it}^{M})\,dQ_{it}^{M} + \sum_{i}\int EXED(TRQ_{it})\,dTRQ_{it} - \sum_{i}\int ES(Q_{it}^{X})\,dQ_{it}^{X} + \\ &+\sum_{i}\left[tax_{it}\times Q_{it}^{M} + outtax_{it}\times TRQ_{it}\right] + \sum_{i}P_{it}^{G}\times Q_{it}^{G} + \sum_{k}P^{L}\times AL_{kt} - P_{GHGt}\times\sum_{g}GWP_{gt}\times GHG_{gt}\Big\} + \\ &+\sum_{k}\lambda_{kt}\left(-\mu\left(\sum_{i}X_{ikt}/L_{kt}\right) + \sigma\left(L_{kt} - \sum_{i}X_{ikt}\right)/L_{kt}\right) - \sum_{i}\delta_{it}\left\{Q_{it} + Q_{it}^{X} + Q_{it}^{G} - \sum_{k}Y_{ikt}X_{ikt} - \left(Q_{it}^{M} + TRQ_{it}\right)\right\} - \\ &-\sum_{i}\pi_{it}\left(\sum_{i}X_{ikt} + AL_{kt} - L_{kt}\right) - \sum_{i}\gamma_{it}\left(\sum_{i}f_{ikt}X_{ikt} - R_{kt}\right) - \sum_{g}\varepsilon_{gt}\left(\sum_{i,k}E_{gikt}X_{ikt} - GHG_{gt}\right) \end{aligned} \tag{44}$$

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In this case, we cannot use the Hamiltonian alone because the constraints are not taken into account. Rather, we maximize the Hamiltonian subject to these constraints by setting up a Lagrangian in which the Hamiltonian is the new objective function (Weber 2011). Therefore, the Lagrangian is then formulated as in Equation 44.

$$\frac{\partial L}{\partial X_{ikt}} = -(1+\rho)^{-t} C_{ikt} - \frac{\lambda_{kt}}{L_{kt}}(\mu+\sigma) + \delta_{it} Y_{ikt} - \pi_{kt} - \\ - \gamma_{kt} f_{ikt} - \varepsilon_{gt} E_{gikt} \leq 0 \quad (45)$$

$$\frac{\partial L}{\partial X_{ikt}} X_{ikt} = 0 \quad (46)$$

Equation 45 shows that in every period, the marginal benefit from additional production activity should equal the marginal costs from using all resources plus the loss of land fertility. Equation 46 ensures that the agricultural activity can result in a positive value only if the land is fully utilized.

$$\frac{\partial L}{\partial L_{kt}} = -(1+\rho)^{-t} \alpha_{kt}(L_{kt}) - \\ - 2\lambda_{kt}(\rho-\mu)\sum_i X_{ikt} L_{kt}^{-2} + \pi_{kt} \leq 0 \quad (47)$$

$$\frac{\partial L}{\partial L_{kt}} L_{kt} = 0 \quad (48)$$

Equation 47 represents the optimal land use in every period by showing that the marginal cost of using land is greater than or equal to the marginal cost of land supply. In this case, the land fertility loss from production activities, represented by a function consisting the shadow price λ_{kt}, production activity X_{ikt}, and land supply L_{kt}, is incorporated into the marginal cost of acquiring land. Equation 48 shows that the land will have a nonzero value only if it is fully employed.

$$\frac{\partial L}{\partial R_{kt}} = -(1+\rho)^{-t} \beta_{kt}(R_{kt}) + \gamma_{kt} \leq 0 \quad (49)$$

$$\frac{\partial L}{\partial R_{kt}} R_{kt} = 0 \quad (50)$$

Equation 49 represents the optimal resource use in every period. The marginal cost of using land is greater than or equal to the cost of land supply. The discount rate plays an important role by enlarging the cost of using land in later periods. Equation 50 ensures that the resource will be valued at zero only if it is not fully employed.

$$\frac{\partial L}{\partial Q_{it}} = (1+\rho)^{-t} \varphi(Q_{it}) - \delta_{it} \leq 0 \quad (51)$$

$$\frac{\partial L}{\partial Q_{it}} Q_{it} = 0 \quad (52)$$

Equation 51 shows that in the later periods, the price paid for the marginal consumption is inflated by the factor $(1 + \rho)^t$ and should be less than the producer's willingness to accept in any period. Equation 52 represents that in any period, the commodity has a nonzero value if the commodity is totally consumed.

$$\frac{\partial L}{\partial \lambda_{kt}} = \sigma\left(L_{kt} - \sum_i X_{ikt}\right)/L_{kt} - \mu\left(\sum_i X_{ikt}/L_{kt}\right) \quad (53)$$

$$\frac{\partial L}{\partial \theta_{kt}} = \lambda_{kt-1} - \lambda_{kt} = 0 \quad (54)$$

where:

$$\lambda_{kt} = \frac{-L_{kt}}{(\mu+\sigma)}\Big[(1+\rho)^{-t} C_{ikt} - \delta_{it} Y_{ikt} + \pi_{kt} + \\ + \gamma_{kt} f_{ikt} + \varepsilon_{gt} E_{gikt}\Big] \text{ if } L_{kt} > 0$$

Equation 53 is the state equation. Equation 54 is the costate equation, implying that for every period t, the shadow price of each agricultural activity X_{ikt} should equate the marginal benefit from production to the marginal production cost plus the loss in fertility.

$$\frac{\partial L}{\partial \delta_{it}} \geq 0 \text{ and} \\ Q_{it} + Q_{it}^X + Q_{it}^G \leq \sum_k Y_{ikt} X_{ikt} + \left(Q_{it}^M + TRQ_{it}\right) \quad (55)$$

$$\delta_{it} \geq 0 \text{ and } \frac{\partial L}{\partial \delta_{it}} \delta_{it} = \Big(Q_{it} + Q_{it}^X + Q_{it}^G - \sum_k Y_{ikt} X_{ikt} - \\ - \left(Q_{it}^M + TRQ_{it}\right)\Big)\delta_{it} = 0\text{ ; } \forall i \quad (56)$$

Equation 55 is the Kuhn-Tucker condition transformed from the balance constraints that hold for every period. Equation 56 shows that the commodity price is zero if the production activity is not fully engaged.

$$\frac{\partial L}{\partial \pi_{it}} \geq 0 \text{ and } \sum_i X_{ikt} + AL_{kt} \leq L_{kt} \quad (57)$$

$$\pi_{it} \geq 0 \text{ and } \frac{\partial L}{\partial \pi_{it}} \pi_{it} = \left(\sum_i X_{ikt} + AL_{kt} - L_{kt}\right)\pi_{it} = 0\text{ ; } \forall k \quad (58)$$

$$\frac{\partial L}{\partial \gamma_{it}} \geq 0 \text{ and } \sum_i f_{ikt} X_{ikt} - R_{kt} \leq 0 \quad (59)$$

$$\gamma_{it} \geq 0 \text{ and } \frac{\partial L}{\partial \gamma_{it}} \gamma_{it} = \left(\sum_i f_{ikt} X_{ikt} - R_{kt}\right)\gamma_{it} = 0\text{ ; } \forall k \quad (60)$$

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Equations 57 and 59 are the Kuhn-Tucker conditions that hold for every period. Equations 58 and 60 indicate that the relationship between the input use and its price exists in every period and that ensures that the land and resource prices are both nonnegative.

$$\frac{\partial L}{\partial \varepsilon_{gt}} \geq 0 \text{ and } \sum_i \sum_k E_{gikt} X_{ikt} - GHG_{gt} \leq 0 \quad (61)$$

$$\varepsilon_{gt} \geq 0 \text{ and } \frac{\partial L}{\partial \varepsilon_{gt}} \varepsilon_{gt} = $$
$$= \left(\sum_i \sum_k E_{gikt} X_{ikt} - GHG_{gt} \right) \varepsilon_{gt} = 0 \;;\; \forall g \quad (62)$$

Equation 61 indicates that with constraining in every period, the net emission from agricultural sectors must be less than or equal to the total emissions. Equation 62 shows that the emission price has positive value only if the activity is fully employed.

DISCUSSION

Long-run development of bioenergy involves many factors such as the objectives of the policy makers, resource availability, land fertility, and market prices of feedstocks and energy. This section compares and analyses the two proposed dynamic agricultural sector models to understand the factors affecting the models, which can provide useful information in the policy analysis and goal determination.

Purpose of bioenergy development

The models show that the effectiveness of the bioenergy development is significantly affected by the goal. Because Taiwan is vulnerable to the sea level rise, the first priority of the bioenergy development for the policy makers may be the GHG emission reduction. Thus, the objective of the long-run planning of the bioenergy development will fall into the model I, implying the welfare will be maximized by selecting the bioenergy technique with the highest offset potential. Intensive agricultural activities may continue if the subsidies are provided to encourage that the idle land is used to plant the energy crops. Model II regards the intergenerational fairness as an important consideration by maximizing the social welfare for all periods simultaneously to ensure that the future generations will not suffer from the intensive agricultural activities engaged in by the current generations. Since future generations cannot speak for themselves, the policy makers must speak for them. Therefore, as shown in Equations 45 and 47, engaging in the optimal agricultural activities in each period must be considered.

Planning period matters

"How long is the long run" must be defined before a policy is constituted and enforced. If it is a ten-year schedule, the key issues for the policy makers might be the net bioenergy production, the change in the farmers' income, or the emission reduction. The governors may want to adopt model I to analyse the stability of the bioenergy supply and the savings from the reduced import of expensive foreign energy under various market operations. However, if the bioenergy is developed to ensure the sustainable growth of the society, maximizing the current welfare by sacrificing future benefits is not desired because the benefits attached to future generations must be incorporated. In such cases, the appropriate land rotation and changes in the existing cultivation patterns may be taken into account, and model II may provide a more useful information.

Change in land fertility must be reasonably estimated

Intensive agricultural activities reduce the land fertility, increase production costs, decrease the competitive power, and therefore result in an unsustainable production pattern. Therefore, a change in land fertility should be incorporated in the long-run planning. A proper land rotation can alleviate such problems by providing adequate economic incentives such as the subsidies or tax credits to encourage farmers to participate in a land rotation program.

Discount rate can change over time

The discount rate is another factor to be incorporated in the long-run analysis. During price increasing periods, the value of every dollar saved today will decrease by the discount rate $(1 + \rho)^t$, meaning that we should not invest unless the expected that the return is higher than ρ. In this sense, model II maximizes the discounted welfare for all periods simultaneously. However, uncontrolled factors such as the economic growth and international political issues make it difficult to obtain an appropriate discount rate. Therefore,

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model II only simulates the possible outcomes under the assumed or plausible expected discount rates, and when the economic condition alters, the adjustments reflecting the changes on discount rates will be necessary.

Exchange between immediate benefit and future income

Model I looks for the optimal solution of the welfare maximization without taking the potential future losses induced by the current practices into account. If the planning horizon is long enough, an important question about how much should we forgive now for the potential welfare gained by our children would arise. Policy makers can compare the welfare effects of different policies for different models, and then design mechanisms or incentives to balance the current losses and future benefits.

CONCLUSION

To reduce the dependence on the imported energy and to alleviate the potential damages caused by the climate change, bioenergy is an attractive option in Taiwan because a substantial amount of land has been released. Owing to the intimate relationship between the bioenergy development and agricultural activities, this study proposes two dynamic agricultural sector models to investigate what factors must be accommodated in the policy analysis.

The analytical result suggests that the land rotation is required to maintain the land fertility and to achieve sustainable development. A proper design of economic incentives such as a direct subsidy or tax credit is important so that the farmers are willing to participate in the rotation program. Moreover, the objectives of the bioenergy development must be defined in advance because the question whether to incorporate the discounted future benefits results in a considerable difference in the analytical framework. In addition, changes in the discount rates and planning horizons can influence the result significantly. Such changes must be considered to evaluate the effectiveness of policies.

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