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Research Article

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Posted Date: June 15th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9669575/v1

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Version of Record: A version of this preprint was published at Waste and Biomass Valorization on August 8th, 2026. See the published version at https://doi.org/10.1007/s12649-026-03747-0.

Simulations of Optimal Biofuel Production and Land-Use Patterns under AR6 Projections and Green Finance Mechanism in Taiwan

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Abstract

The study employs a stochastic, recursive model to identify optimal biofuel production and land-use change under AR6 and green finance policies in Taiwan. The results show that (1) significant climate impacts would decrease total biofuel production from 185.7 to 149.9 million gallons and substantially change cropping patterns, but residual utilization, depending on the level of climate impacts, offers a reliable lower bound (40.77%–50.46%) of total biofuel production; (2) green bond mechanism improves biofuel production by lowering investment and operating costs, and the sufficient green bond volume should range from $840–$1,120 million to support qualified biofuel producers. The current size of the green bond market is insufficient for optimal biofuel development; (3) the inefficient emission trade system would incur a loss of $10.89–$23.24 million to biofuel producers; and (4) approximately 15,100 hectares of cropland would be set aside, and about 69,500 hectares of currently abandoned land would be converted into production.

Keywords: bio-hydrogen energy, land distribution, shared socio-economic pathway, stochastic programming.

1. Introduction

Rapid economic growth has made living standards substantially better in the past decades, but it also comes with invisible costs such as reduced quality of water resources [1,2], species extinction [3], and global warming [4–6], all of which deteriorate the environment and make it unsustainable [7]. While some of the detrimental effects, such as loss of soil fertility [8], are reversible, most, such as increased concentrations of greenhouse gases (GHGs) and induced climate change, cannot be reversed at least in the foreseeable future. GHG emissions are caused by the unprecedented increase in the use of fossil fuels, and their transferable properties result in transboundary impacts such as climate change, a global concern. Under such considerations, countries have imposed emission taxes on fossil fuels and provided numerous economic incentives for green development, including reforestation, promotion of green products, recycling and reutilization of municipal solid waste, and renewable energy [9–11].

Taiwan has been particularly interested in developing bioenergy in recent years for three reasons. First, bioenergy development could reduce dependence on foreign energy and improve energy security. Second, carbon sequestration from bioenergy utilization may contribute to climate change mitigation, thereby likely delaying the detrimental effects of sea-level rise and avoiding future severe climate impacts [12,13]. Third, as a member of the World Trade Organization since 2005, Taiwan has set aside substantial cropland amid global competition, enabling the conversion of idle and fallow cropland back into production. To encourage the full utilization of agricultural resources and promote bioenergy production, the government launched the "*White Papers of Energy Transformation*" in 2022 [14], which specifies the type of bioenergy to be developed, the amount of subsidy and feed-in tariff to be applied, and the goals of emission reduction to be achieved from various sources.

Mounting studies on bioenergy have been conducted in Taiwan [15–17]. Tso et al. [18] employ a life-cycle assessment to calculate the biofuel conversion ratios for sweet potato, food corn, and sweet sorghum. They point out that the energy input-output ratio for these crops is generally greater than 1; thus, using them to produce biofuel can be beneficial. Fei and Kung [19] illustrate that the subsidy policy would encourage bioenergy development. However, because agricultural practices are complex and cropping decisions are influenced by various

factors [20–22], this study cannot adequately guide large-scale biofuel development. Additionally, the climate shift in Taiwan is substantial, and farmers' past cropping decisions may change considerably in the future. Thus, alterations should also be incorporated to explore the socio-economic effects [23,24] fully. However, the *White Paper* further points out that since much of local biofuel information is insufficiently rigorous, Taiwan's bioenergy development's primary focus was biopower.

This study aims to provide information on how biofuel contributes to energy security and how climate impacts and green finance applications may affect biofuel production strategy. Specifically, we analyze the crops and crop residues available for biofuel in Taiwan and incorporate these input possibilities into a stochastic, recursive, partial-equilibrium mathematical programming model to delineate the development efficiency and emission offsets from biofuel strategies. First, we account for climate factors using the AR6 (Shared Socio-economic Pathway (SSP)) projections from the Central Weather Bureau of Taiwan [25] to examine potential yield changes across different climate scenarios. Second, we examine how cropping decisions, associated biofuel production, and land use would be altered under each scenario. Finally, we discuss the necessary size of the green bond market to support efficient biofuel production.

This analysis bridges the gaps between climate's environmental and economic effects for two reasons. First, unlike previous climate projections such as HADCM and AR4, the AR6 projections consider the socio-economic impacts. Thus, the AR6 pathways better reflect the actual economic and environmental effects in the face of inevitable climate change. Second, previous biofuel studies generally focus on how bioresources can be converted into bioenergy, and the process involves multiplying the available resources by their energy content. While this approach is valid when the scale is small or when everything remains constant, it is unlikely to hold when climate change alters the foundations of all agricultural activities. Therefore, combining the most recent climate projections (AR6) with a sectoral analysis (i.e., stochastic programming) is essential to assess the actual biofuel potential when environmental and cropping decisions are altered simultaneously.

This study would contribute by incorporating alternative input options and environmental risks into the analysis. First, the results indicate that while climate impact would affect crop

yields and substantially change cropland use, crop residuals can be used to sustain net biofuel production. The results would thus be a valuable addition to previous studies that separately focus on the possibility of climate impacts [26] or on climate impacts on agriculture and resource allocation [20,21]. Second, the results indicate that green bond application can improve biofuel production efficiency while maintaining sustainable cropping patterns. This result would benefit the design of promotional policies and the development of the green finance market [29–31], both of which can be used to attract a broader range of potential participants.

2. Literature Review

Climate change mitigation is key to achieving societal development and sustaining environmental sustainability because it has resulted in numerous environmental problems, such as intensified heat waves and snowstorms [22,23], accelerated retreat of glaciers and ice caps [24,25], increased occurrence and strength of hurricanes and typhoons [26,27], all of which have substantial impacts on local and global communities. For example, Ku et al. [28] note that typhoon-induced surges would significantly increase coastal disaster risk amid population growth and urbanization, particularly in Asian countries such as South Korea and China. Pastor and Khodayar [29] further point out that climate change would also cause marine heat waves and induce long-term ocean warming, which would affect the water cycle. Therefore, to alleviate the intertwined environmental and economic impacts of climate change, a transition from fossil to renewable energy must be placed to decrease atmospheric CO_2 concentrations.

Bioenergy is an attractive option because it produces biofuel for vehicles and biopower for electricity. Its production relies on agricultural resources; thus, the supply of input feedstocks can be adequately planned and predicted, reducing the uncertainty of the final output [30,31]. Indeed, converting biomass into energy requires additional input during processing. Wang [32] employs the well–to–wheel analysis and indicates that biofuel production would yield a positive energy balance. Subsequently, Tso et al. [18] and Cao et al. [33] demonstrate that high-carbohydrate crops such as sweet sorghum and sweet potato can be valuable in biofuel production and improving energy security. However, there are also acute criticisms of biofuel because the use of feedstock in energy production has led to a sharp decrease in corn exports,

causing massive fluctuations in food markets and, in turn, sudden land-use change [43,44], further intensifying "food–energy" conflicts.

In the face of climate change, this conflict could become even more severe, as crop production does not respond as expected to changes in temperature and precipitation [34,35]. For instance, Burke and Emerick [35] find that corn yields may decrease by up to 15 percent with an additional 30 days of exposure to higher-than-average temperatures. Skevas et al. [36] and Kung et al. [37] further simulate the effects of yield change on cropping patterns. They find that as long as farmers expect changes in temperature and precipitation, the cropping decision will change, and crop supply could vary significantly. Since biofuel production is highly dependent on agricultural activities [38,39], it is crucial to incorporate climate impacts, yield changes, and land-use changes into biofuel studies to reflect these factors [40–42].

In general, biofuel can be produced by crops and crop residuals. For crops such as corn, sugarcane, and sweet potato, which contain more carbohydrates, biofuel can be produced at low cost, but using these crops is likely to reduce food supply and, subsequently, lead to price fluctuations in global food markets [43,44]. In recent years, cellulosic technology for converting lignocellulosic biomass (i.e., crop residuals) has been widely discussed [45,46]. Kocak et al. [47] note that innovations in biofuel technology would alleviate pressure on the energy–food nexus. However, the production costs of cellulosic technology remain high, and more financial support is needed to make it successful. Under such circumstances, this study examines how conventional and cellulosic biofuel technologies complement each other and whether crop residuals can reduce the impacts of climate change and the transfer of cropland.

3. Methodology

Figure 1 illustrates how agricultural activities, biofuel supply, and climate impacts are interrelated and why these factors should be integrated simultaneously into the analysis. When there is no biofuel production, the equilibrium ends up at a land price of $\boldsymbol{P}$, the land demand of $\boldsymbol{Q}$. When biofuel becomes feasible, energy crops will now compete with food crops, thereby driving up the land price to $\boldsymbol{P_1}$ and the amount of total land supplied increases to $\boldsymbol{Q_1}$, which is equal to the land used by energy crop ($\boldsymbol{EQ_1}$) and food crops ($\boldsymbol{Q_2}$).

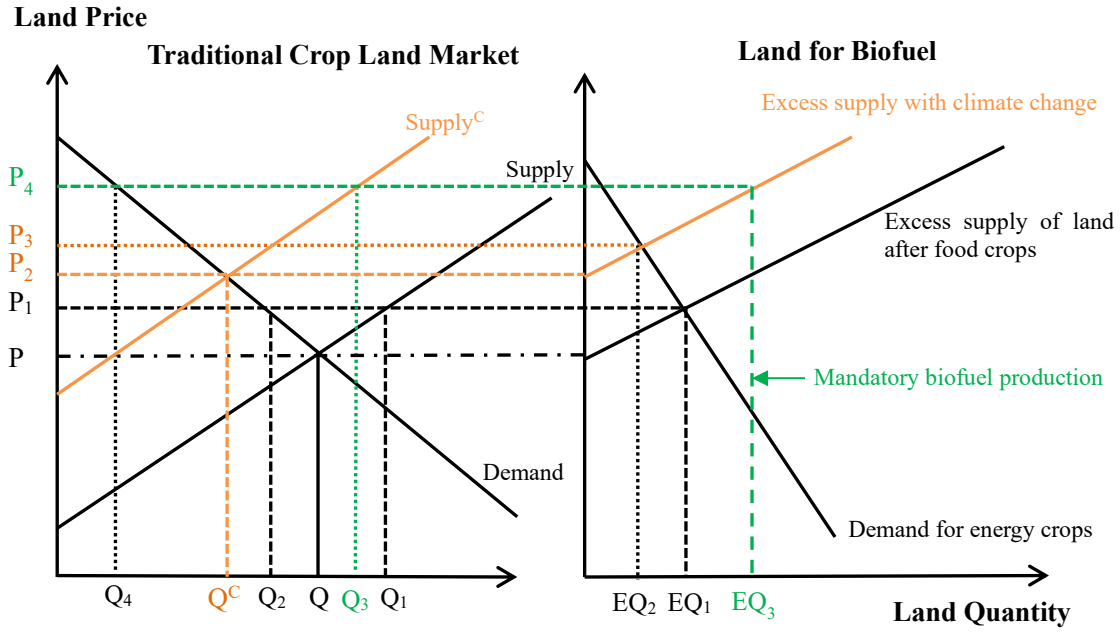


Figure 1. Effects of biofuel development on land use under climate change

Thus, even if the total land to be utilized increases, the land used for food crops decreases by Q-Q_2. The total land use is Q_1, but food crops would be used only in Q_2. Therefore, a portion of cropland currently planted with food crops will switch to energy land, and the total land use for energy crops will become Q_1-Q. Climate impacts are also likely to affect the supply curve similarly. The new equilibrium under climate change is P_2 and Q^c, but the existence of biofuel production will drive up the land price to P_3 with a land requirement of EQ_2. When the government enforces strict environmental regulations (e.g., a tax on gasoline or an ethanol-blend requirement), the effective land requirement of energy crops will move to EQ_3 with a land price of P_4. Subsequently, land for food crops will further decline to Q_4, and total energy land will expand to Q_3-Q_4. This study aims to quantify the impacts of these effects.

3.1 Model formulation

We have shown that biofuel production would further increase land prices and shift land use in response to yield changes. Therefore, a sector-wide analytical framework should be applied to address this issue. Because changes in biofuel regulation and land use would be reflected in alterations to consumer and producer surplus, we can focus on determining the market equilibrium that automatically calculates social welfare [48]. This approach has been proven useful in environmental management and resource allocation studies and is particularly important in policy analysis [49–51].

Since climate-induced yield change is uncertain, this study develops a stochastic mathematical programming model to investigate the problem. The objective function that maximizes the welfare from agricultural activities, biofuel production, and climate risks is expressed as Equation (1):

$$\boldsymbol{Welfare} = Prob_s * \{\sum_i \int \omega(CONQ_i)dCONQ_i - \sum_{ip} \int \alpha_{ip}(CROPLAND_{ip})dCROPLAND_{ip} -$$
$$\sum_{ip} \int \gamma_{ip}(LABOR_{ip})dLABOR_{ip} - \sum_i \sum_p \sum_n PROCOST_{inp}\, CROPPROD_{inp}\} -$$
$$\sum_i \int EXCESSD(Q_i^M)dQ_i^M + + \sum_i \int EXED(TRQ_i)dTRQ_i - \sum_i \int EXCESSS(Q_i^X)dQ_i^X +$$
$$\sum_i (tax_i * Q_i^M + outtax_i * TRQ_i) + \sum_i REP_i^G REQ_i^G + \sum_P LANDSUB^L SUBLAND_P +$$
$$\sum_j ENGSUB_j ENGLAND_j - EMIP_{GHG} \sum_g EMIF_{gip} EMISSION_{gip} \quad (1)$$

where the $\boldsymbol{Prob_s}$ is the probability of yield change occurring at each state of nature, $\boldsymbol{CONQ_i}$ calculates the area under the demand curve of the $\boldsymbol{i^{th}}$ crop, $\boldsymbol{\alpha_{ip}(CROPLAND_{ip})}$, and $\boldsymbol{\gamma_{ip}(LABOR_{ip})}$ indicate the inverse demand curve of land and labor used for crop $\boldsymbol{i}$ in region $\boldsymbol{p}$, respectively. Along with other input costs ($\boldsymbol{PROCOST_{inp}}$), each crop's area under the supply curve can be calculated. $\boldsymbol{Q_i^m}$ is the amount of import, $\boldsymbol{Q_i^x}$ is the amount to be exported, and $\boldsymbol{TRQ_i}$ stands for the import quota limitation of crop $\boldsymbol{i}$, respectively. Combined with tariffs ($\boldsymbol{tax_i}$ and $\boldsymbol{outtax_i}$), government supportive policies ($\boldsymbol{REP_i^G}$), and emission value ($\boldsymbol{EMIP_{GHG}}$), the market equilibrium of agricultural commodities and biofuel production can be depicted by the objective function. Some demand-supply balance constraints also applied to the objective function:

$$CONQ_i + Q_i^X + REQ_i^G \leq \sum_p (CROPYIELD_{ip} CROPPROD_{ip}) + Q_i^M + TRQ_i \quad \forall\, i \quad (2)$$

Equation (2) is a constraint forcing the use of commodities not to exceed its production plus import. The term $\boldsymbol{CROPYIELD_{ip}}$ reflects the potential yield change while $\boldsymbol{CROPPROD_{ip}}$ Indicates the harvest area of crop $\boldsymbol{i}$ at place $\boldsymbol{p}$.

$$\sum_i CROPLAND_{ip} + SUBLAND_p - LANDAVAIL_p \leq 0 \quad \forall\, p \quad (3)$$
$$\sum_i \mu_{ip} PRIPROD_{ip} + \sum_i \rho_{ip} SECPROD_{ip} \leq INPUTAVAIL_p \quad \forall\, p \quad (4)$$

Similarly, equation (3) balances the land use, while equation (4) represents the inputs such as labor, fertilizer, and irrigation used to produce primary and secondary commodities in each production region p must not exceed total purchase plus inventory. The $\boldsymbol{\mu}$ and $\boldsymbol{\rho}$ are the usage coefficients of different production processes.

$$\sum_{i,p} EMIF_{gip}\, EMISSION_{gip} \leq NETEMI_g \quad \forall\, g \tag{5}$$

Biofuel production reduces carbon emission, but the total reduction should not exceed the total emission (i.e., the product of the global warming potential (***EMIP$_{gip}$***) and emission type (***EMISSION$_{gip}$***), as specified in equation (5).

3.2 Scenario setup

In this study, four energy crops and crop residuals are used to produce biofuel while accounting for climate impacts on crop yields. Sweet potato and poplar are identified as energy crops, while corn straw and rice stover are collected as crop residuals. The climate impacts addressed in this study focus on changes in temperature and precipitation that substantially affect agricultural activities. Thus, four common AR6 Shared Socio-economic Pathway (SSP) scenarios (i.e., SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) are used to assess potential influences on crop yield.

With this setup, we can examine how market conditions, especially for changes in gasoline prices and emission trade prices, affect the production pattern of biofuel. The range of energy and emission prices used in the simulations is based on their average historical prices. The gasoline price to be simulated is set up between \$0.625 to \$1.25 per liter, with an increment of 3.13¢ per liter. For emission trade prices, because Taiwan lacks a mature trade mechanism and emissions are generally traded on foreign climate exchanges such as the Chicago Climate Exchange and the Singapore Climate Exchange, we use their average historical trade prices to simulate the emission effect. Notably, the emission trade has rapidly increased due to international conflicts, and the range of per-metric-ton CO_2-equivalent prices is between \$0 and \$50 to reflect this impact on biofuel production. The model is validated in Table 1.

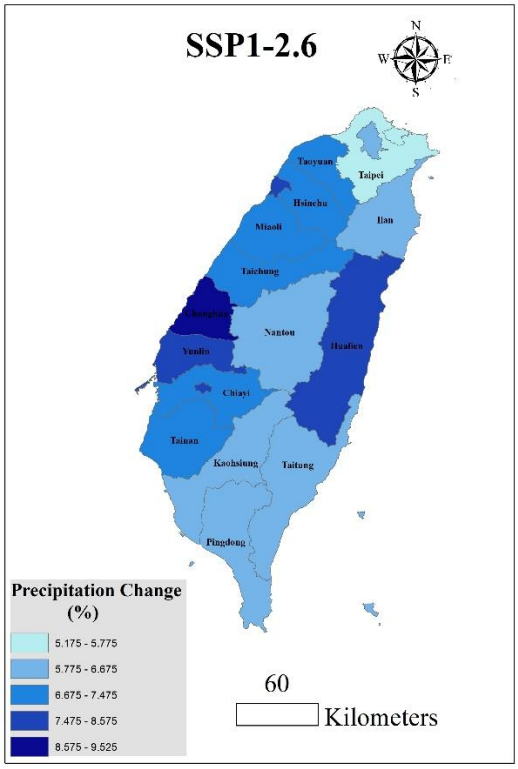
Table 1 demonstrates the model's applicability by comparing 2022 agricultural data with simulation results. The results show that the model will likely delineate Taiwan's agricultural system, as the deviations between observations and simulations are slight. Thus, we may conclude that the model used in this study could be appropriate. Subsequently, the model is extended to a stochastic structure to account for environmental risks to crop yields.

Table 1. Model validation

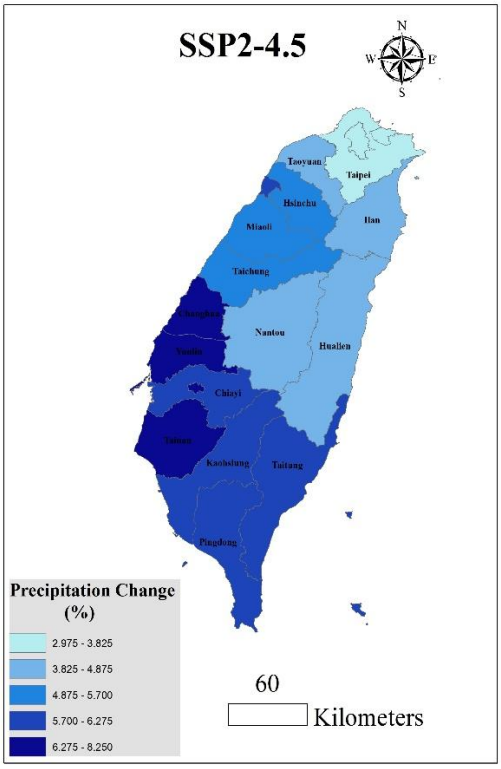
	Output (ton)		Price ($/kg)	
Commodity	Observation	Deviation	Observation	Deviation
Rice	1,333,018	0.32%	0.899	3.54%
Corn	167,908	1.94%	0.176	-0.22%
Peanut	58,066	-19.56%	1.163	-7.33%
Hog	864,792	-0.19%	2.780	-1.17%
Broiler Chicken	304,354	3.87%	1.883	1.51%
Native Chicken	266,161	1.36%	2.867	0.69%
Egg	7,018,647	-0.28%	5.97*	0.02%

*Price per 100 eggs

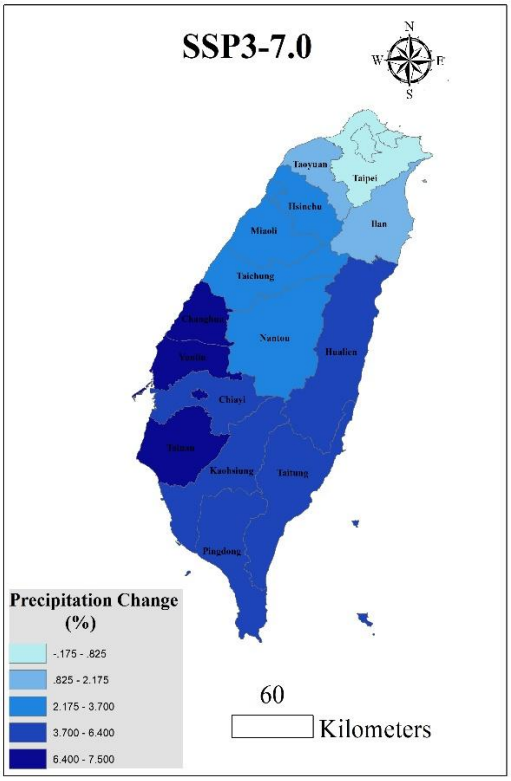
Figure 2 shows projected climate impacts on precipitation and temperature in Taiwan. Figure 2(a) shows that climate change will likely increase rainfall in southern Taiwan, and Figure 2(b) indicates that northern Taiwan may experience a warmer climate. Taiwan is getting warmer and more humid, possibly altering current agricultural practices and biomass supply. Furthermore, the unequal regional climate impacts indicate that changes in cropping decisions would not be uniform. Thus, it is also likely to affect Taiwan's agricultural market substantially. Therefore, in the following sections, we will examine climate-induced yield changes and use these estimates to simulate the sectoral equilibrium of the agricultural and biofuels sectors.



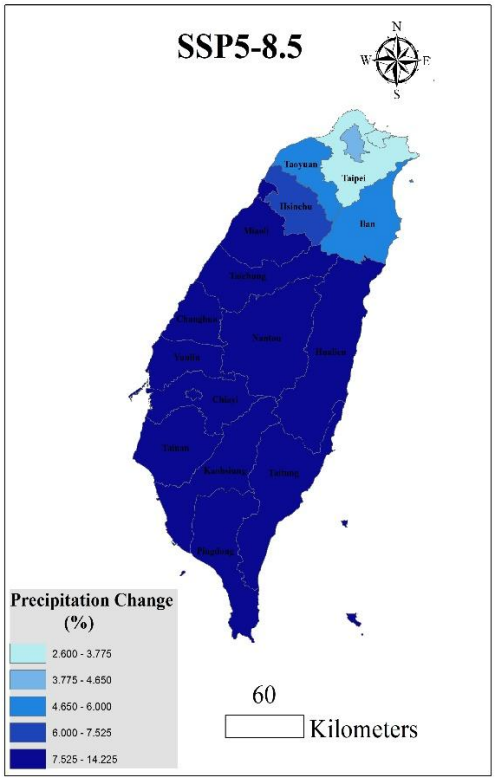
2(a):SSP1



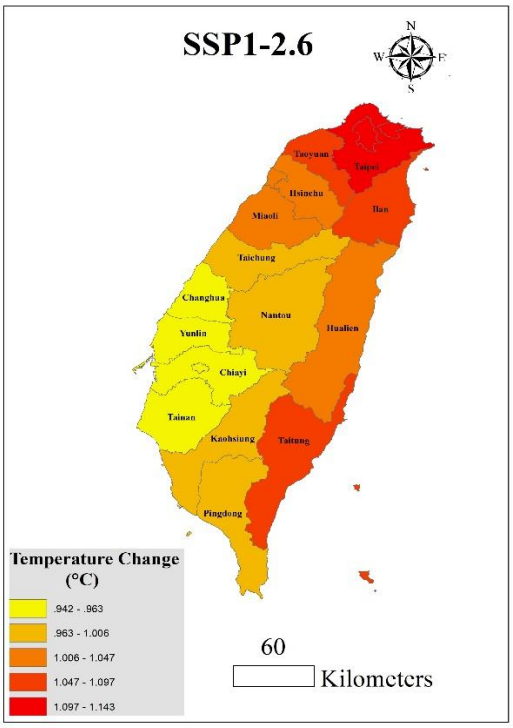
2(a):SSP2



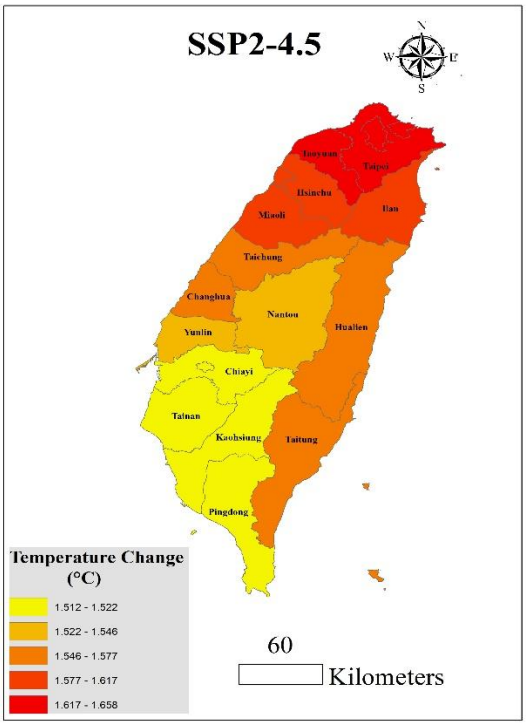
2(a):SSP3



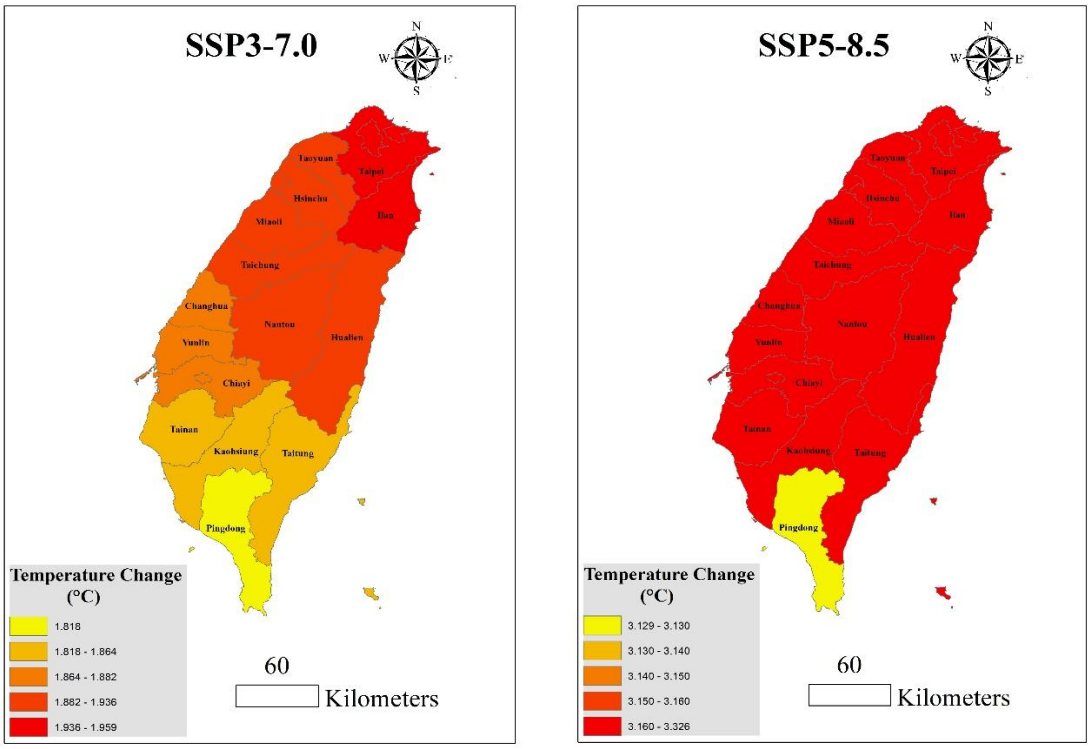
2(a):SSP5



2(b):SSP1



2(b):SSP2



2(b):SSP3 **2(b):SSP5**

Figure 2. Changes in temperature and precipitation under SSPs. Fig. 2(a) shows changes in rainfall, and Fig. 2(b) presents possible changes in Taiwan's temperature under various atmospheric CO_2 concentrations.

Given the significant climate impact, historical crop yields should not be used; instead, we need to estimate probable crop yields for each climate scenario to simulate farming decisions, biomass supply, and biofuel production. By comparing the climate scenarios of HADCM, AR5, and AR6, we see that yields of all crops will be significantly affected, with effects more pronounced when climate impacts are severe. The estimation approach is based on Chang et al. [1], who regressed crop yield on climate factors and obtained estimates of yield changes under the HADCM projections. Here, we update the parameters using the AR5 and AR6 projections with 1980-2020 agricultural data. Under different climate impacts, crop yields would vary substantially. While the effect on crop yield is slight when global warming is not severe, it becomes apparent when atmospheric CO2 concentration remains high.

Table 2. The estimated crop yield change (%) under various climate projections

		HADCM		***AR5***				**AR6**			
Group	Products	**A2**	**B2**	***RCP26***	***RCP45***	***RCP60***	***RCP85***	**SSP1**	**SSP2**	**SSP3**	**SSP5**
Rice	Rice	-0.71	-1.66	-1.83	-1.76	-1.90	-2.88	-1.22	-1.29	-1.38	-2.05
Cereal	Corn	-1.24	-3.02	-3.30	-3.21	-3.45	-5.19	-2.20	-2.38	-2.59	-3.78
	Wheat	0.15	0.09	0.17	0.08	0.12	0.24	0.09	0.00	-0.09	0.01
	Sorghum	7.16	17.90	19.42	19.07	20.44	30.64	13.03	14.23	15.62	22.55
Pulses	Soybeans	3.76	2.86	4.86	2.62	3.59	6.96	2.65	0.55	-1.43	1.17
	Peanuts	-0.03	0.95	0.76	1.08	1.03	1.30	0.60	1.03	1.44	1.58
	Adzuki bean	-2.63	-10.13	-10.04	-11.02	-11.39	-16.22	-7.07	-8.99	-10.98	-14.08
Roots	Sweet-Potatoes	-2.26	-2.76	-3.77	-2.75	-3.29	-5.64	-2.26	-1.43	-0.67	-2.40
	Potatoes	0.97	3.17	3.24	3.43	3.58	5.19	2.24	2.72	3.21	4.27
Special	Tea	-1.65	-1.45	-2.29	-1.37	-1.79	-3.33	-1.29	-0.45	0.34	-0.83
	Cane for process	1.03	-1.87	-0.84	-2.28	-1.92	-1.80	-0.98	-2.66	-4.30	-4.01
	Cane for fresh	1.03	-1.87	-0.84	-2.28	-1.92	-1.80	-0.98	-2.66	-4.30	-4.01
	Sesame	1.14	-5.07	-3.38	-5.92	-5.40	-6.18	-3.00	-6.13	-9.18	-9.33
Vegetables	Radish	1.14	1.67	2.13	1.70	1.96	3.23	1.32	1.02	0.75	1.67
	Carrot	-0.31	7.34	5.79	8.35	7.98	10.00	4.64	7.98	11.28	12.26
	Ginger	1.71	6.38	6.36	6.93	7.18	10.26	4.46	5.63	6.83	8.82
	Scallion	0.81	9.69	8.46	10.82	10.69	14.17	6.39	9.73	13.06	15.06
	Garlic bulb	5.25	5.89	8.33	5.80	7.08	12.36	4.91	2.77	0.79	4.73
	Leek	-1.44	1.96	0.64	2.45	1.96	1.60	0.95	3.03	5.05	4.54
	Bamboo	-1.20	2.90	1.57	3.47	3.02	3.10	1.60	3.87	6.08	5.85
	Asparagus	2.37	-1.18	0.62	-1.72	-1.00	0.22	-0.24	-2.82	-5.30	-4.13
	Water bamboo	2.37	-1.18	0.62	-1.72	-1.00	0.22	-0.24	-2.82	-5.30	-4.13
	Cabbage	-1.02	-0.05	-0.72	0.11	-0.18	-0.87	-0.25	0.62	1.46	0.87
	Cauliflower	-1.02	-0.05	-0.72	0.11	-0.18	-0.87	-0.25	0.62	1.46	0.87
	Cucumber	-1.90	-2.69	-3.47	-2.73	-3.17	-5.25	-2.14	-1.59	-1.11	-2.62
	Bitter	0.89	7.80	6.97	8.67	8.63	11.59	5.19	7.68	10.16	11.90
	Tomato	-1.03	1.69	0.69	2.08	1.72	1.55	0.86	2.47	4.04	3.71
	Pea	-0.38	-1.65	-1.60	-1.80	-1.85	-2.60	-1.14	-1.50	-1.86	-2.34
	Watermelon	-2.72	-1.10	-2.72	-0.80	-1.54	-3.68	-1.29	0.63	2.46	0.73

Banana	-2.04	-7.51	-7.50	-8.16	-8.46	-12.09	-5.26	-6.61	-8.00	-10.36
Pineapple	-1.35	-11.40	-10.22	-12.67	-12.62	-16.98	-7.60	-11.19	-14.77	-17.35
Ponkan	-0.28	0.55	0.26	0.67	0.57	0.55	0.29	0.77	1.23	1.16
Tankan	0.55	8.79	7.55	9.85	9.67	12.71	5.76	8.95	12.13	13.83
Wentan	2.02	5.94	6.21	6.38	6.74	9.89	4.25	4.96	5.72	7.82
Liucheng	2.52	2.25	3.53	2.13	2.77	5.13	1.99	0.72	-0.47	1.33
Lemon	1.02	-3.11	-1.86	-3.68	-3.27	-3.54	-1.77	-3.97	-6.12	-6.02
Grapefruit	-1.69	-7.19	-7.01	-7.85	-8.06	-11.37	-4.98	-6.50	-8.06	-10.16
Mango	-6.46	-4.12	-7.69	-3.60	-5.29	-10.85	-4.04	-0.10	3.63	-0.72
Betel	-0.94	-8.43	-7.52	-9.38	-9.33	-12.51	-5.61	-8.31	-11.01	-12.88
Guava	1.25	3.38	3.60	3.62	3.85	5.70	2.44	2.76	3.10	4.35
Wax apple	1.96	14.86	13.46	16.48	16.48	22.29	9.95	14.45	18.95	22.43
Grape	5.23	0.91	4.25	0.18	1.64	5.39	1.72	-2.49	-6.51	-3.37
Plum	1.55	3.27	3.71	3.44	3.76	5.79	2.43	2.44	2.49	3.90
Peach	0.84	3.53	3.45	3.85	3.96	5.59	2.45	3.18	3.94	4.98
Persimmons	1.32	4.97	4.95	5.40	5.59	7.98	3.47	4.39	5.34	6.88
Apricot	2.40	0.87	2.32	0.59	1.25	3.11	1.08	-0.66	-2.32	-0.81
Carambolas	1.13	-1.05	-0.10	-1.37	-1.01	-0.58	-0.43	-1.86	-3.24	-2.76
Pear	0.11	-2.53	-1.99	-2.88	-2.75	-3.45	-1.60	-2.75	-3.89	-4.23
Apple	-5.72	-22.86	-22.51	-24.91	-25.68	-36.43	-15.90	-20.44	-25.09	-31.98
Papaya	-2.13	-4.74	-5.30	-5.01	-5.44	-8.30	-3.50	-3.61	-3.79	-5.75
Sugar apple	-2.99	-7.26	-7.94	-7.72	-8.30	-12.49	-5.30	-5.72	-6.21	-9.07
Passion fruit	-2.47	-9.21	-9.18	-10.01	-10.37	-14.81	-6.44	-8.13	-9.86	-12.73
Coconut	-3.05	-5.64	-6.65	-5.88	-6.54	-10.28	-4.28	-3.96	-3.73	-6.37

Table 2 presents potential changes in crop yield under different climate change scenarios in Taiwan. In addition, since the AR6 projections are the most recent and account for socio-economic factors, the AR6 estimates of crop yield change will be used in the following analysis. The results also show that climate change may increase or decrease the yield depending on the projected SSP level. Farmers who recognize this may adjust their cultivation to maintain their expected income, which may not necessarily come from the sale of energy biomass. Therefore, we will incorporate these estimates of average crop yield changes into the simulation model to evaluate how biofuel production profiles vary and how crop residuals can be used to sustain biofuel production under different climate conditions.

3.3 Data

The data used in this study include climate and weather statistics [52], Monthly Price Statistics, and the Agricultural Yearbook of Taiwan [53], along with energy and emissions information derived from reports released by the European Climate Exchange and the Taiwan Bureau of Energy [14]. The demand and supply of crops are based on publications from the Taiwan Ministry of Economics. At the same time, Chen and Chang [64] and Chang et al. [1] collected detailed price elasticities for products. The authors update the crop yield estimates with the AR5 and AR6.

4. Results

In this section, we will present the results of the following issues: (a) the total biofuel production at different climate impact levels, (b) the emission offset ratio from different sources, (c) contributions of crop residuals on total biofuel production, (d) required size of the green bond market, and (e) the potential transfer among cropland, aside land, and fallow land. We then compare the results with previous studies to examine the aggregate effects of climate change on Taiwan's biofuel production and to provide applicable policy recommendations.

4.1 Biofuel production strategies

Table 3 presents the essential information on Taiwan's biofuel data. The estimates must be incorporated into the simulation model alongside crop production data, as crop yield, planting seasons, labor requirements, irrigation needs, and fertilizer use vary across processing regions. That is, a biomass with a higher ethanol conversion rate does not necessarily mean it is the

most suitable feedstock; instead, the biomass that yields the highest social benefit would be the most suitable.

Table 3. Biofuel processing data in Taiwan

		Sweet Potato	Poplar	Corn Stover	Rice Straw
Crop density	%	20	10	15	25
Hauling cost	$/ton biomass	4.75	7.27	5.30	5.22
Acquisition Cost	$/ton biomass	62	67	14.5	14.5
Production cost	$/kWh	0.34	0.38	0.42	0.43
Ethanol	% of biomass	12.5	15.1	9.5	9.1
CO_2 offset	kg/kg biomass	0.14	0.32	0.12	0.12

Source: [53–56]

Fig. 3 displays the base result of Taiwan's biofuel production. Since emission offsets in Taiwan are not internationally tradable, the emission price in the base scenario is set to zero (while the international market has a high price), and biofuel production generally responds to changes in the substitute product (i.e., gasoline). The results show that when the offset value is not adequately recognized by the market (i.e., zero emission price), biofuel production is approximately 499 million liters at the current gasoline price, which would increase to 624 million liters at the gasoline price of $1.25/liter or decrease to 390 million liters when the gasoline price declines to $0.625/liter.

The results indicate that all energy biomass could be used for biofuel production, depending on gasoline prices. For example, poplar has high acquisition and hauling costs, so producers will use it as a feedstock only when gasoline prices are above $0.97/liter. Due to their low production and processing costs, sweet potato, corn stover, and rice straw would be utilized at almost all price levels. However, corn stover's contribution is low relative to sweet potatoes and rice straw because corn's total production area is small. The results also indicate that while sweet potatoes are a useful feedstock and their supply is positively related to gasoline prices, rice straw can still be a desired energy source, as it can be acquired in substantial amounts at low cost.

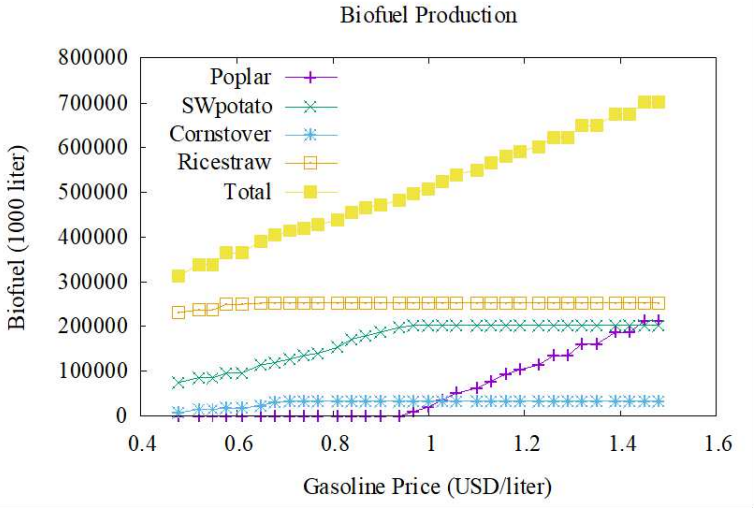
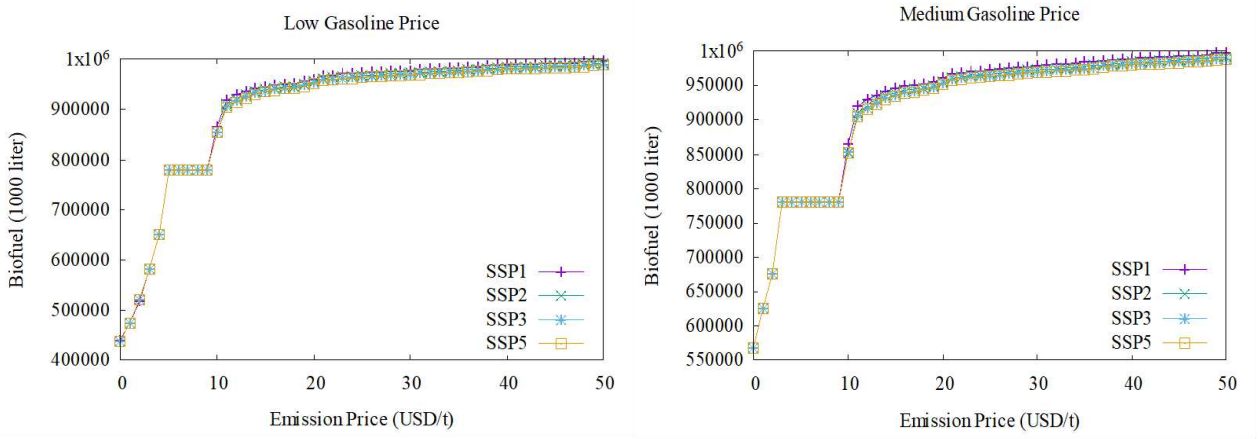


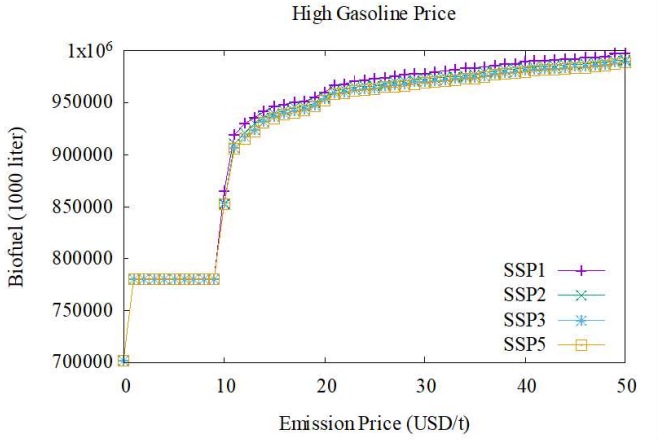
Figure 3. Biofuel production when the emission trade is not possible.

Fig. 4 compares the total biofuel production under alternative SSP projections. In this section, we assume that the emission offset is domestically tradable and examine how biofuel production responds to this. The price of emission offsets in the U.S. is about $200 per metric ton (MT), but it is generally lower in Asian countries and regions. Thus, we assume the price range for emission trading is between $0/MT and $50/MT for each climate projection. Because emission offsets are attached to some values, biofuel producers receive higher profits, thereby expanding total production.

It is evident that gasoline prices affect the expansion rate. Fig 4(a) shows that it requires a $6/MT emission price to expand biofuel production to 785 million liters, but only a $4/MT at a mid-gasoline price level (Fig 4(b)) and $2/MT at a high gasoline price level (Fig 4(c)) to reach the same output. However, at a higher emission price (i.e., greater than $10/MT), total biofuel production would approach 0.98 billion liters, regardless of the gasoline price level. This result implies that the biofuel potential from these feedstocks is extracted at a high enough emission trade price that an upper bound is reached.



4(a) **4(b)**



4(c)

Figure 4. Biofuel production under various SSPs and gasoline prices. Fig. 4(a) indicates the total biofuel production when gasoline is lower than the current market price, Fig. 4(b) shows the biofuel production at the current market price, and Fig. 4(c) presents the biofuel production when the gasoline price is high.

The results indicate that the influence of climate change on biofuel production is trivial. While, indeed, a substantial climate change scenario (i.e., SSP5) would cause biofuel production to decline, the decrease is relatively small compared to the minor climate change scenario (i.e., SSP1), which contradicts the results found by Brown and Brown [57] and Kung [58] who claim that a severe climate change would induce high emission price and more biofuel should be produced. Thus, the findings in Fig 4 merit more discussion.

First, our study incorporates not only biofuel production under market conditions but also changes in crop yields substantially altered by climate change. Since we assume that farmers will adjust cropping decisions to maximize or, at least, maintain income, a crop whose yield is significantly affected by climate change is likely to have a higher price in the next period, and

thus, the farmers may plant more of this crop rather than focusing on the supply of biofuel feedstocks. However, the more significant the climate impact is projected to be, the greater the influence on crop yields is expected, and thus, the SSP5 scenario has somewhat lower biofuel production than SSP1.

Second, land transfer is another factor causing the shifts in biomass supply. We have shown that under various SSPs, regional temperatures and precipitation vary substantially, implying that cropland previously suitable for a specific crop may no longer be able to cultivate that crop in the next period. An even worse case is that the marginal cost of cultivating the land exceeds the commodity price, leading farmers to set aside or abandon that land. Thus, a sudden shift in land use due to climate impacts could also affect the supply of biofuel feedstocks. These two reasons, taken together, result in a significant deviation from the biofuel potential reported in past studies.

4.2 Source of emission offsets

Since biofuel is produced from energy crops (e.g., sweet potatoes and poplar) and crop residuals (e.g., corn stover and rice straw), we can investigate the offset contribution of each source. Fig. 5 displays the results. The total emission offset from biofuel production ranges from 54,500 to 116,200 tons per year, depending on climate projections and energy and emission prices.

The emission offset capacity from different biomass sources also varies considerably when market conditions change. Fig. 5(a) shows that at a low gasoline price, approximately 68% of total emission reduction comes from crop residues, and 32% from using energy crops. As emission prices increase, the offset ratio for energy crops continues to rise, reaching $6/ton. Fig 5(b) has a similar pattern but a minor divergence. In a scenario with current gasoline prices, using energy crops would contribute 45% of total emission reduction, with crop residuals accounting for 55%, and a mere $3/ton emission price is required to make energy crops dominant. The reason for this result is apparent: higher gasoline prices stimulate biofuel production, leading to more energy crops being produced and used, thereby increasing total emissions from energy crops. When gasoline prices go even higher, as depicted in Fig 5(c), using energy crops will contribute 55%-65% of total emission reduction, regardless of the emission price.

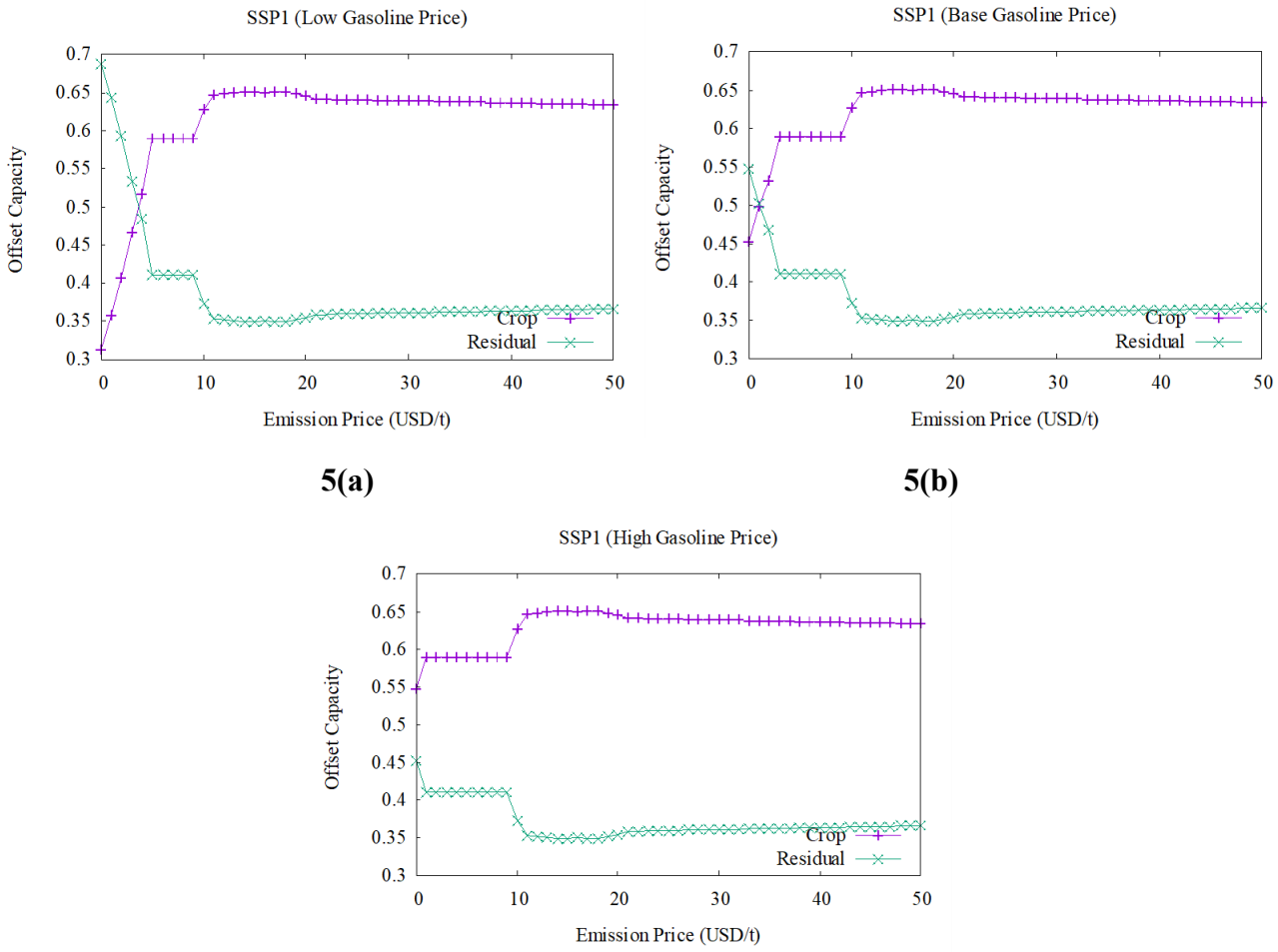


Figure 5. Emission offset contribution from energy crop and crop residuals. Fig 5(a) shows the low gasoline price scenario, Fig 5(b) presents the offset ratio at the base gasoline price, and Fig 5(c) shows the offset ratio when the gasoline price is high.

The results offer valuable insights for biofuel suppliers and decision-makers. First, whether crop residuals or energy crops should be used as the primary energy source depends on expectations for gasoline and emission prices. While crop residuals are generally less expensive than energy crops, they provide fewer emission offsets per ton of biomass. At higher emission prices, the gains from residual-based emissions may be significantly lower, so unless the marginal cost of using energy crops is higher than that of residuals, producers will be discouraged from using this source.

Second, the constancy of biomass supply does matter. Producers can generally collect crop residues from seasonal crops at a lower cost, and the supply of corn stover and rice straw is relatively stable because a substantial portion of the land is used for rice and corn production. In contrast, the acquisition cost of energy crops is high because it involves land preparation,

plowing, planting, and harvesting, and producers cannot determine the precise commodity output to be delivered to the biofuel processing plant. These impacts may be significant in Taiwan, where typhoons occur frequently. Therefore, unless energy and emission prices are attractive, it is unlikely that farming decisions will change substantially. Using residuals would be a better option in low-price scenarios.

4.3 Reliance on crop residuals

Figure 6 delineates the resource dependency of biofuel production, and this result would help decision-makers review the importance of crop residuals in Taiwan's biofuel development. At a low gasoline price (Fig. 6(a)), crop residual contributes approximately 72% of total biofuel production, and energy crops contribute 28%. This gap shrinks as gasoline prices rise. The divergence in Fig. 6(b) shows that, at the current gasoline price, biofuel production from crop residuals declines to 63%, while crop-based biofuel production increases to about 37%. In Fig. 6(c), where the gasoline price is $1.25/liter, residual-based biofuel to total production would decline to 57%, and crop-based ethanol can contribute 43%. Collectively, the results show that crop-based biofuel will become more attractive as gasoline prices rise. As the price of emissions increases, producers will tend to supply more crop-based biofuel. Given land and other resource constraints, crop-based biofuel could eventually account for 52% of total production, while residual-based biofuel could account for 48%.

Another issue that merits more discussion is the use of crop residuals. While crop-based biofuel production and associated emission offsets will dominate at higher emission prices, the use of crop residuals guarantees the lower bound of the total biofuel supply. The reason for this argument is that the acquisition cost of crop residuals is generally lower, and producers can still make profits even with low emission prices. While the lower energy conversion rate of crop residuals (76% for corn stover and 72.8% for rice straw, relative to sweet potatoes) may somewhat reduce profits, crop residuals would play an essential role in biofuel production when the emission value is not properly recognized.

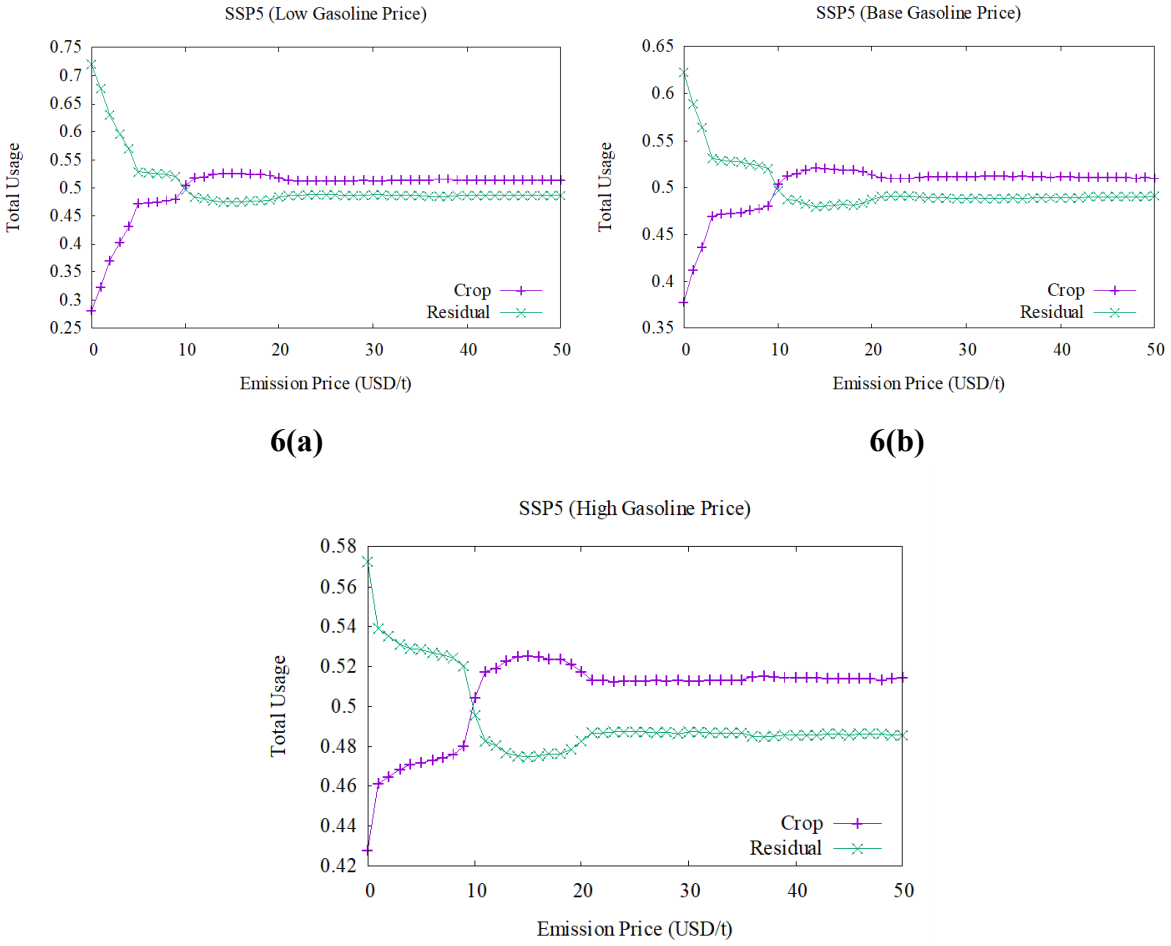


Figure 6. Residual dependency on Taiwan's biofuel production. Fig 6(a) shows the reliance of crop residuals on biofuel production at a lower than the going gasoline price, Fig 6(b) indicates how crop residuals contribute to total biofuel production at the ongoing gasoline price, and 6(c) shows the ratio of residual-based biofuel on total production at a high gasoline price.

4.4 Required size of the green bond market

Based on Figures 3-6, two insights merit further discussion. First, a substantial biofuel expansion will occur at an emission price of more than $2/ton, reaching its maximum production when the emission price exceeds $10/ton, implying that the economic incentive for the environmental benefits is tied to biofuel development. Therefore, an appropriate emission trading system (ETS) should be developed in Taiwan to make this realization possible; otherwise, the large-scale development of biofuels may not reach its potential. Second, while energy crops have a higher energy conversion and emission offset rate and will be the primary input in most cases, using crop residues to produce biofuel is cheap and sustains the biofuel industry in the face of low energy and emission prices. In other words, while crop-based biofuel

increases the upper bound of total production, residual-based biofuel would put up the lower bound of production, and the biofuel suppliers can remain in the industry with positive profits. This result is particularly important for Taiwan's biofuel development because investing in biofuels is costly, and a lower bound can effectively reduce firms' investment risk.

However, since Taiwan does not participate in many international organizations and its carbon offsets are not generally recognized by the Verified Carbon Standard (VCS), emission offsets associated with biofuel production can be traded domestically only. Nevertheless, the regional ETS is not well-functioning in Taiwan. Thus, an appropriate promotion of a green finance market that lowers the production cost would offer another economic incentive for biofuel producers. Table 4 shows the results for an initial borrowing rate of 7% and the biofuel suppliers' annual production costs under different market prices. It is evident that at higher biofuel prices, total production expands, implying that if producers expect such prices, they must invest in additional capacity. Thus, the total production cost will increase. However, this cost burden could be alleviated by using green bonds.

Table 4. The difference between the total production cost and the green bond market

	Gasoline Price			**Emission Price**		
	\$0.48/liter	\$0.97/liter	\$1.45/liter	\$10/ton	\$30/ton	\$50/ton
Biofuel (1000 liter)	312,000	499,200	702,000	780,000	972,577	997,656
by source						
SWPotato	73,962	203,681	203,263	267,364	289,783	322,209
Poplar	0	9,343	212,564	225,783	372,906	351,352
Cornstover	6,677	33,182	33,179	33,859	38,717	44,398
Ricestraw	231,361	252,994	252,994	252,994	271,171	279,697
Production Cost (million \$)	**787.1**	**1,326.3**	**1,614.9**	**1,812.2**	**2,148.8**	**2,252.7**
Bond rate at 6% (million \$)	738.12	1,243.77	1,514.41	1,699.44	2,015.09	2,112.53
Bond rate at 5% (million \$)	690.66	1,163.80	1,417.04	1,590.16	1,885.52	1,976.69
by source						
SWPotato	202.3	557.2	556.0	731.4	792.7	881.4
Poplar	0.0	13.3	303.2	322.0	531.9	501.1
Cornstover	30.0	149.1	149.1	152.1	173.9	199.5
Ricestraw	554.8	606.7	606.7	606.7	650.3	670.7
Green Bond (million \$)	800	800	800	800	800	800
Insufficiency (million \$)	12.9	-526.3	-814.9	-1,012.2	-1,348.8	-1,452.7
Cost Reduction 1 (million \$)	48.98	82.53	100.49	112.76	133.71	140.17
Cost Reduction 2 (million \$)	96.44	165.5	197.86	222.04	263.28	276.01

Note: Investment is assumed to be a 15-year bond with a 7% interest rate, while Cost Reduction 1 is a borrowing rate of 6%, and Cost Reduction 2 is a 5% borrowing rate**.**

At borrowing rates of 6% or 5%, annual production can decrease by \$48.98-\$140.17, or \$96.44-\$276.01 million, depending on the scale of biofuel production. However, according to

Taiwan's green bond data [59], the average amount of green bonds issued for renewable energy from 2019 to 2021 is approximately $800 million. Therefore, a larger green bond market that reduces firms' operating risk may be essential to enabling large-scale biofuel development. The right columns indicating changes in emission prices assume that the emission offset attached to biofuel is tradable, and that gains from emission trade would eliminate investment risks. To explore complex development strategies, it is necessary to investigate the combined effects of ETS, the green bond market, and other economic conditions.

4.5 Land-use transfers

If the emission reductions associated with biofuel production can be realized, it will encourage producers to supply more biofuel. Under such circumstances, the biofuel supplier needs to acquire more energy crops for expansion, thereby driving up their prices. Since the residual supply is relatively stable and a direct long-term approach to increasing biomass is to plant more energy crops, eventually, total cropland supply must increase, as previously demonstrated in Fig. 1. To get more insights into land-use change, we further analyze the changes in cropland supply and investigate how marginal land (i.e., previously cultivated but currently aside and abandoned land) may be utilized under the aggregate influences of climate impacts, market conditions, and biofuel development.

Fig. 7 shows the conversion between cropland and arable land. In the face of changes in crop yields, land use in Taiwan has heterogeneous effects. In most cities, farmers will switch land back into use when they perceive yield changes; they are likely to act on the expectation of changes in commodity prices due to shifts in market supply. This effect is more significant in the regions where agriculture is the primary industry. For example, the cities of Tainan, Yunlin, Chiayi, and Pingtung collectively convert approximately 56,500 hectares, or 19.97% of aside land, into cropland, implying that climate change indeed has a substantial effect on commodity supply and prices, inducing farmers to make such a considerable conversion of previously considered unprofitable aside land.

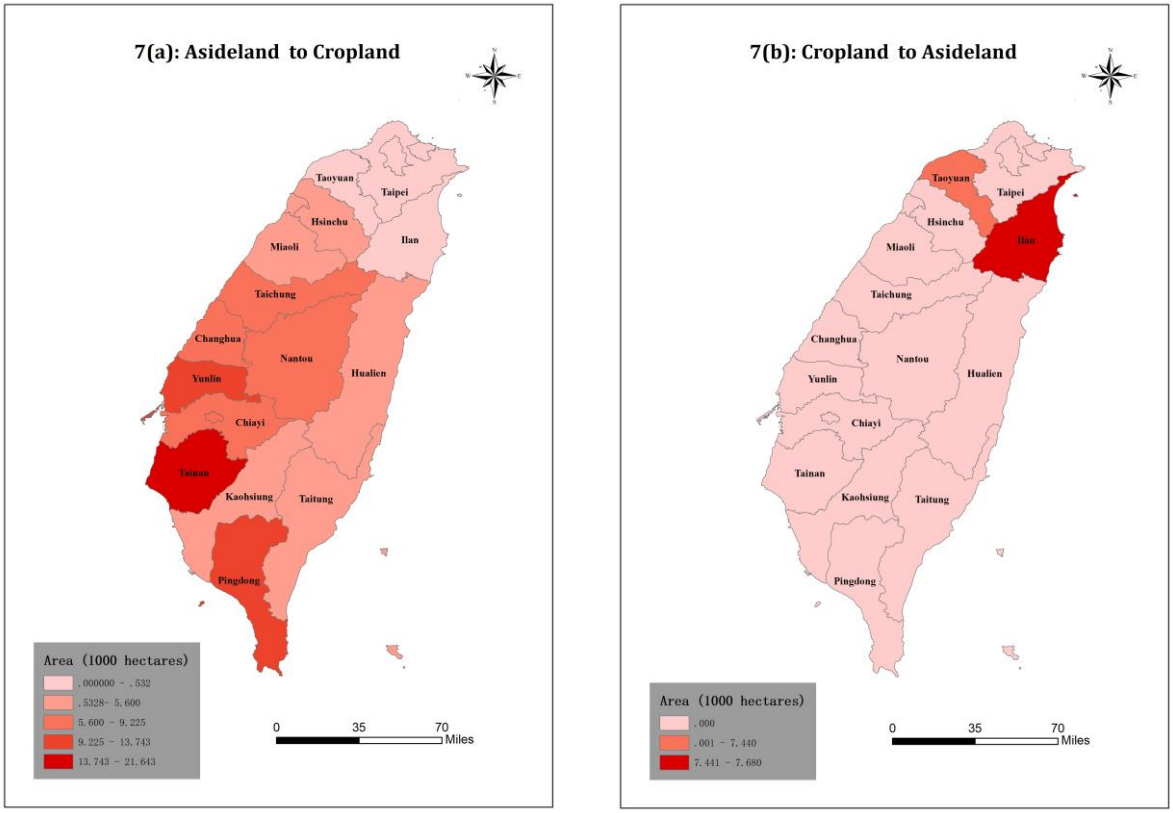
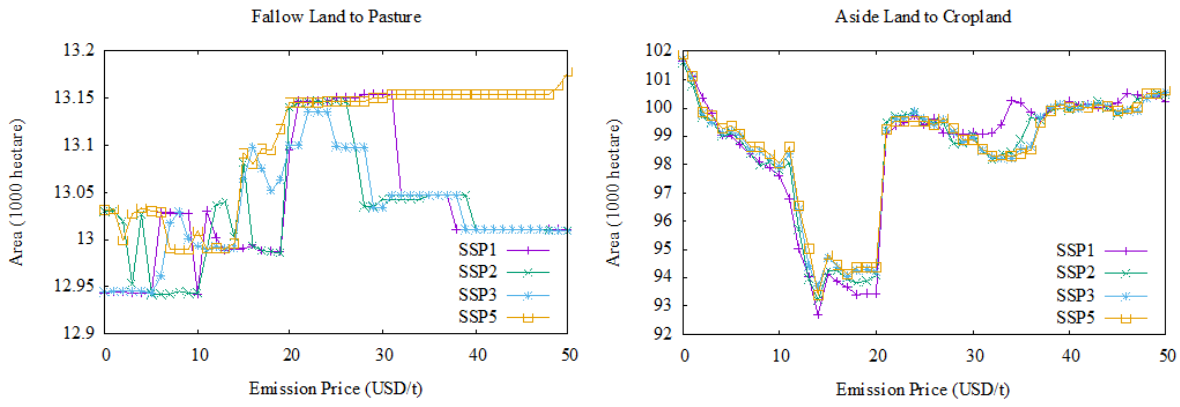


Figure 7. Land-use change in current gasoline and emission prices

Nevertheless, such a conversion of aside land does not occur in northern Taiwan. Specifically, the three most northern cities, Taipei, Taoyuan, and Ilan, set the current cropland to idle. This result indicates that past cropping patterns were not sustainable under climate change, and the outputs of some croplands cannot cover production costs. Under such circumstances, approximately 15,100 hectares of cropland will be set aside in these cities. There is caution in using this result because the impacts on commodity supply stem from climate impacts and are also partly driven by increased demand for energy crops.



8(a) **8(b)**

Figure 8. Potential increase in cultivable land supply. Fig 8(a) shows the land transfer from fellow to pasture, while Fig 8(b) presents the land transfer of aside land to cropland.

There is also a need to investigate how constraints on land supply may be released in the context of biofuel development, given the environmental risks. The results are displayed in Figure 8. Fig. 8(a) indicates that about 13,000 hectares of currently abandoned land will be converted for potential use, depending on the expectations on future market conditions. While the abandoned land is not directly converted into cropland but into pastureland in the short run, the results indicate that total cropland may increase due to biofuel production. This is observed by noting that the amount of converted land gradually increases as emission prices rise. Conversely, Fig. 8(b) shows that biofuel production would stimulate a conversion of aside land to cropland, but such a conversion would first decrease due to climate impacts. However, as the emission price increases to more than $20/MT, the benefits from planting energy crops can be substantial and thus induce a higher conversion on the aside land. The results have some insights. First, it implied that constraints on land resources may be relaxed, allowing more biofuels to be produced. Second, it points out that the marginal land that is not cultivated now will be used in the future to sustain commodity production. When climate impacts become severe, more abandoned land will be switched back into use to secure the food supply.

4.6 Policy Implications

This study has analyzed how climate change may affect biofuel production, crop uses, emission offset, and land-use change. Based on these results, some valuable and applicable policy implications can be derived.

The first policy recommendation is that biofuel expansion should not rely solely on crop residuals. While Kung and Zhang [60] indicate that the use of crop residual would benefit biofuel production to some extent, and Dumortier [61] shows that biofuel studies should take uncertainty associated with biomass production into account to reflect the exogenous impacts on agriculture to what extent the crop residual could benefit biofuel production under climate change and how market conditions may alter biofuel development is rarely integrated. In this study, we explicitly note that the use of crop residuals does not primarily drive biofuel expansion; rather, it is primarily driven by the value of emission offsets. Since the emission value attached to residual-based biofuel is relatively lower than that of crop-based biofuel,

residual-based biofuel is less sensitive to changes in emission prices, but it is more sensitive to changes in acquisition and processing costs. However, it does indeed raise the lower bound for Taiwan's biofuel potential. For this reason, the government should not only focus on subsidizing biofuel products but also assist biofuel suppliers in securing access to crop residuals, so that lower-cost biofuel can be produced when energy and emissions prices are lower.

Another policy suggestion derived from the results also merits more attention. Chen et al. [62] show that if the government correctly supports energy crop cultivation, approximately 300 million liters of biofuel can be produced. Bialek and Unel [63] further demonstrate that bioenergy subsidies can significantly expand total production. However, such a subsidy costs the entire society, and the welfare consequences of wealth distribution have not been thoroughly studied. Thus, even if subsidies increase biofuel production, it is not clear whether this expansion benefits society. This study shows that market operations can adjust biofuel production; in most cases, total output meets demand. The government should focus more on the stability of energy and emission prices rather than on direct subsidies. The expenses on subsidy can be decreased, and the funds can be used to establish non-for-profit but environmentally friendly projects to increase total social welfare.

Finally, climate change will induce substantial land-use changes in Taiwan, and the cropping patterns used to evaluate total biofuel potential must be adjusted accordingly. Taiwan's Ministry of Agriculture has been working to improve farmers' incomes and has offered various promotion policies to assist farmers whose cropland is set aside due to global competition. Alexander et al. [64] and McCarl [50] note that, in the face of global warming, a more detailed analysis is needed to understand the relationships among food supply, population growth, and bioenergy production. This study delineates the effects of climate change, agricultural practices, and biofuel development. The administrative authority in Taiwan should take steps to accommodate these changes. Providing subsidies for crops whose yields have significantly declined and for land whose productivity is greatly affected would be one way to better assist farmers.

5. Conclusions

This study investigates Taiwan's biofuel potential and how its development may be affected

under uncertain climate patterns. This study obtains several significant results by applying a stochastic programming model.

First, some biofuel subsidies should be decreased or terminated because they cannot effectively promote expansion. This suggestion sounds weird, but it is reasonable in Taiwan, where limited land is highly used for various agricultural purposes. The most effective way to increase biofuel supply is to make the realization of emission offset possible. While Taiwan is not a member of the United Nations and cannot trade its emission offsets internationally, a domestic emission trading system can still be designed and operated to at least partly alleviate this difficulty and encourage producers.

Second, whether the climate-induced yield change benefits or harms Taiwan's agriculture is uncertain because this impact shows regional heterogeneity, making a quick conclusion difficult. In this study, we show that as long as farmers perceive environmental effects on their production, they will respond to these changes by adjusting their cropping decisions and converting more land to maintain income streams. Policies that help farmers promptly incorporate this information would be beneficial.

This study has some limitations that future research may improve. For example, the financial risks associated with large-scale biofuel development are not discussed. The risks could be significant in biofuel production because it involves a vast lump-sum payment at the beginning stage. If biofuel suppliers' discount rates are substantial, they are unlikely to invest, especially given Taiwan's lack of an effective emissions trading system. Furthermore, the model assumes that environmental impacts arise solely from climate change. Other extreme events, such as typhoons and frequent floods in Taiwan, could also make substantial short-run influences that increase uncertainty. Future studies may consider this concern in exploring Taiwan's biofuel potential further.

Data Availability

Data will be available upon request.

Conflict of Interest

The authors declare there is no conflict of interest.

Acknowledgements
The authors thank the National Natural Science Foundation of China (72163006), the Major Program of the National Social Science Foundation of China (24VHQ018), and the Key Program of the National Natural Science Foundation of China (72033005).

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