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An assessment of climate risks on the stability of biomass supply and biofuel production

CHIH-CHUN KUNG[1]*, *KAIGE MA*[1], *JUAN LI*[2]

[1]*Institute for Interdisciplinary Research, Shandong University, Weihai, P.R. China*
[2]*School of Mathematics and Statistics, Shandong University, Weihai, P.R. China*

**Corresponding author: cckung78@sdu.edu.cn*

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Abstract: Global warming has altered regional temperatures and precipitation, potentially leading to deviations from planned biofuel production and emission-reduction targets. This study revisits the market equilibrium of agricultural and biofuel production under climate risk, using updated IPCC projections. It employs a two-stage stochastic programming model to examine the overall effect of climate change on Taiwan's biofuel production. The results indicate that biofuel production depends on the level of climate impact and emission prices. In addition, total input use is generally between 2.79 and 4.72 million tonnes. The higher the gasoline price, the sooner the producer will exhaust its production capacity. While Taiwan could sustain biofuel production when gasoline and emission prices are high, a substantial land-use change would occur. Approximately 74 500–81 900 hectares of idle land will return to production. However, the increase in cropland supply may not lead to biofuel expansion, as it has a limited ability to offset emissions.

Keywords: bioenergy; climate change; representative concentration pathway; stochastic programming

The primary cause of climate change is the extensive use of fossil fuels that emit greenhouse gases (GHGs) into the atmosphere, reducing heat reflection and increasing the globe's average temperature. McCarl (2006) demonstrates that the average global temperature increased by approximately 0.5 °C during the 20th century. Since climate change would result in many environmentally unsustainable phenomena, including sea-level rise, glacier retreat, desertification, and an increased likelihood of extreme events (IPCC 2018), it is necessary to reduce fossil fuel use and make more substantial commitments to renewable energy (Kung 2018).

Taiwan has limited fossil fuel reserves and must import more than 99% of its energy needs; thus, it is highly vulnerable to fluctuations in energy prices. Taiwan's administrative authority promulgated strict environmental regulations in 2015 to reduce the use of petroleum and thermal coal (Taiwan Ministry of Economic Affairs 2018). Given these restrictions, it is evident that Taiwan needs to explore new sources to meet its fuel demand. Under such circumstances, Taiwan has been particularly interested in biofuel development since 2016 (Kung 2018).

While biofuel has been widely studied and utilised, many studies focus on net biofuel production (Cao et al. 2017), input-output analysis (Tso et al. 2009), or socio-economic effects (Kaoma and Gheewala 2021). Still, climate factors that influence the foundations of feedstock supply are not accommodated in such studies.

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Based on the Representative Concentration Pathways (RCPs) projections from the Central Weather Bureau (2023), Taiwan's future temperatures and precipitation are expected to vary substantially over the next few decades. Consequently, the Council of Agriculture in Taiwan has encouraged farmers to incorporate climate risks into their crop decisions. Since biofuel production depends on agricultural activities, changes in agrarian practices under different climate impacts must be incorporated to achieve a reliable and comprehensive biofuel study (Mounir et al. 2019).

This study bridges the gap by accommodating the latest IPCC projects to analyse how climate change affects biofuel development. This concern arises from two reasons. First, the climate-induced shift in temperature and precipitation would alter crop yields, thereby changing farmers' expected income. Thus, investigation of cropping patterns is warranted. Second, biofuel development is costly, and whether producers are willing to expand depends on market conditions and climate. Therefore, integrating these factors into a single study is crucial for a comprehensive analysis of biofuels.

The study aims to examine how Taiwan's biofuel development is affected by climate change impacts through changes in agricultural practices. It incorporates these changes into a two-stage stochastic mathematical programming model to simulate the market equilibrium of both farming and biofuel markets. Since biofuel is considered a substitute for gasoline, whose price fluctuates over time, we also examine how changes in gasoline prices affect producers' production strategies and offset net emissions. We would evaluate the potential effects of land-use transfer to determine the climate's impact on long-run biofuel production.

The study would contribute to the literature on renewable energy development and climate change mitigation in several ways. First, while Cammarano et al. (2016) indicate that climate change would alter land productivity, the flows of cropland and fallow land are not presented. We show how climate shifts change cropping decisions, leading to land-use switches, so biofuel producers can forecast fluctuations in biomass supply and adjust their production strategies accordingly. Second, while biofuel is used to improve energy security and mitigate climate change (Mounir et al. 2019), it rarely discusses how biofuel production is affected by land-use change and climate change. By integrating climate change, energy, and emission prices, we can provide information on the amount of fossil fuels replaced by biofuel, the economic incentives received by biofuel suppliers, and the environmental benefits from biofuel production.

MATERIAL AND METHODS

Climate change, primarily induced by the increased concentration of anthropogenic greenhouse gas emissions, has caused several environmental problems, such as a rise in sea level (Arnall and Hilson 2023), the retreat of glaciers (Mohammadi et al. 2023), more frequent and stronger hurricanes (Snaiki and Parida 2023), and increased frequency in heat waves (Lee et al. 2020), all of which would incur substantial costs. Therefore, a consensus is that replacing fossil fuels with renewable energy sources is the top priority in the coming decades (Kung and Wu 2020).

Research background

Geographically, Taiwan has a land area of about 36 000 km^2, of which 65% is mountainous (Taiwan National Statistics 2020). Because cropland is scarce in Taiwan, it has been intensively engaged in various agricultural practices (Taiwan Council of Agriculture 2023). After Taiwan joined the World Trade Organisation, the cropland set aside increased rapidly from 68 000 hectares in 2001 to approximately 280 000 hectares in 2012 (Taiwan Council of Agriculture 2020). The release of cropland enables bioenergy production in Taiwan. Biofuel is the only liquid energy source that directly replaces gasoline and diesel.

Khanna and Crago (2012) show that biomass production is directly related to agricultural practices, and the rapid increase in input demand may cause a sudden shift in land-use change. Whether biofuel can mitigate climate change is unclear. Thus, farmers' cropping decisions may switch from food crops to energy crops. Kung and Wu (2020) assess probable yield changes to estimate total biofuel production, but this approach does not indicate what might occur under different climate patterns. Therefore, a well-defined sectoral mathematical programming approach that identifies optimal resource allocation would be beneficial.

Methods

To integrate agricultural, energy, and climate factors, we demonstrate their theoretical interrelationships and then define a stochastic mathematical programming model to simulate the results.

Theoretical background. Studies have indicated that climate change is likely to alter crop yields and lead to changes in land use. Thus, it is essential to understand how such variations in cropping and land-use decisions would affect biofuel production and other socio-economic components. Assuming *ceteris paribus*, the potential influence of climate change and biofuel production is shown in Figure 1. At a prevailing land price of P, the land demand is Q. When the energy crop competes with land, it drives the land price to P_1. Therefore, a portion of cropland currently planted with food crops will be converted to energy land, and the total land use for energy crops is the difference between Q_1 and Q_3.

When the government enforces strict environmental regulations (e.g. a tax on gasoline or ethanol-blend requirements), market demand for biofuel shifts outward, driving land prices to P_2. Subsequently, total land used increases to Q_4, and land for food crops declines to Q_2. Thus, the difference between Q_2 and Q_4 is specified as 'Energy Land*' in the figure on the right. Climate impacts are also likely to affect the supply curve similarly; this study aims to quantify these effects to facilitate the efficient development of biofuels. However, the biomass supply for food commodities and biofuel production is subject to climate-induced changes in temperature and precipitation. Since crop yields under climate change can be either positive or negative, depending on crop type and region, the expected equilibrium for each crop would vary, and past equilibria would be unstable.

Theoretical model formulation. According to the theoretical framework, we quantify the overall effect by calculating the area between the demand and supply curves (Samuelson 1952). The resultant objective function that simultaneously accommodates land-use change and biofuel production is expressed as Equation (1).

This objective function is also subject to the following constraints:

$$\begin{aligned} &Household_i + RepurQ_i^G \le \\ &\le \sum_p \left(Cropyield_{ip} CroppingD_{ip} \right) \quad \forall\, i \end{aligned} \tag{2}$$

where: $Cropyield_{ip}$ – output of i^{th} crop in region p

Equation (2) is the balance constraint that forces total demand (i.e. household consumption and government purchases) to be smaller than total supply (i.e. production). Here, we use the domestic market as the base formulation. In an open economy, international trade should include both imports and exports.

$$\sum_i Fland_{ip} + ECland_p - Landtype_p \le 0 \qquad \forall\, p \tag{3}$$

where: $Landtype_p$ – the land type in region p

$$\begin{aligned} &\sum_i \mu_{ip} Primary_{ip} + \sum_i \rho_{ip} Secondary_{ip} \le \\ &\le Inputavail_p \quad \forall\, p \end{aligned} \tag{4}$$

where: $Secondary_{ip}$ – the i^{th} secondary commodity output in region p; $Inputavail_p$ – the amount of available inputs in region p; μ, ρ – the processing coefficients of primary and secondary commodities, respectively

Equation (3) forces the sum of different land use to be less than the total land available, and Equation (4) represents the constraints on other resource uses, including the labour, fertiliser, and irrigation of primary and secondary commodities in each production region p.

$$\begin{aligned} Welfare = {} & Prob_s \times \Big\{ \sum\nolimits_i \int \omega(Household_i) dHousehold_i - \sum\nolimits_{ip} \int \alpha_{ip}(Land_{ip}) dLand_{ip} - \sum\nolimits_{ip} \int \gamma_{ip}(Farmlabour_{ip}) dFarmlabour_{ip} - \\ & - \sum\nolimits_i \sum\nolimits_p \sum\nolimits_n Processcost_{inp} CroppingD_{inp} \Big\} + \sum\nolimits_i RepurP_i^G RepurQ_i^G - \sum\nolimits_g GWP_g Emiprice_g Emioutput_{gip} + \\ & + \sum\nolimits_{iP} Fsubsidy_i FLand_{iP} + \sum\nolimits_j ECsubsidy_j ECland_{jp} \end{aligned} \tag{1}$$

where: $Prob_s$ – the probability that climate impact occurs; $Household_i$ – the household demand for i^{th} crop; $Land_{ip}$ and $Farmlabour_{ip}$ – the land and labour use of crop i in region p, respectively; $Processcost_{inp}$ – the processing costs from n^{th} possibilities; $CroppingD_{inp}$ – cropping decisions of farmers in different areas; $RepurP_i^G$ – government repurchase price; $RepurQ_i^G$ – repurchase quantity; $Emiprice_g$ – emission value; GWP_g – the global warming potential of emission source g; $Emioutput_{gip}$ – the emission output; $Fsubsidy_i$ – the agricultural promotion policies such as subsidies on food commodities; $ECsubsidy_j$ – energy crops; $Fland_{iP}$ – the land used for i^{th} food commodity in region p; $ECland_{jp}$ – the land used for j^{th} energy crops in region p; γ, α and ω – the inverse demand curves of household consumption, inverse supply curve of land, and inverse supply curve of labor, respectively

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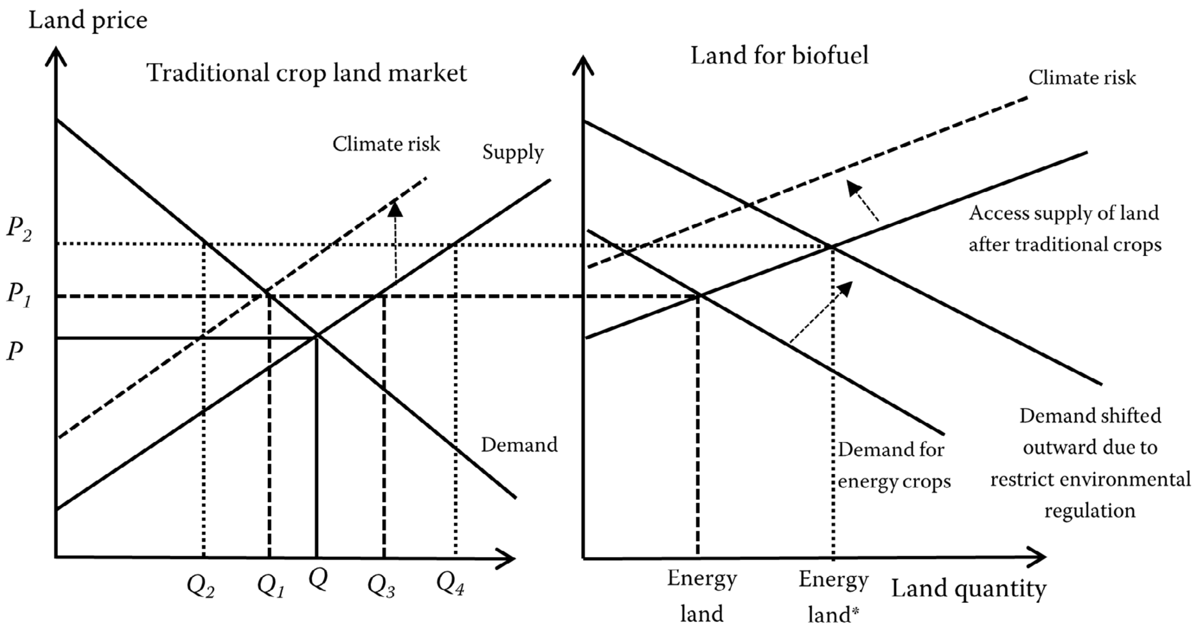


Figure 1. Aggregate effects of biofuel development on biomass supply

Source: Authors' own elaboration

It indicates that the use of inputs must be less than the sum of their endowments and purchases in all regions, given the usage coefficients of μ and ρ.

$$\sum_{i,p} Emifactor_{gip} Emioutput_{gip} Emiprice_g \leq \\ \leq Totalemission_g \quad \forall g \tag{5}$$

where: $Emifactor_{gip}$ – the emission factor of g^{th} greenhouse gases from i^{th} crop in p region; $Totalemission_g$ – the net emission of g^{th} greenhouse gas

The production of biofuel provides environmental benefits, and thus, Equation (5) constrains the emission reduction from this source. It allows the value from the emission offset to be included in the analysis. Given the nature of price endogeneity, the optimal condition can be derived using the Lagrangian and Kuhn–Tucker conditions.

$$\frac{\partial L}{\partial CroppingD_{inp}} = -\left(\sum_i \sum_p Processcost_{inp}\right) + \\ + \gamma_1 \left(1 + Yieldchange_i\right) \sum_p Cropyield_{ip} \tag{6}$$

where: $Yieldchange_i$ – the yield change of crop i; L – the form of Lagrangian

Equation (6) is the condition for the optimal production of all crops. It is determined by the sum of production cost and the marginal value of production, where the latter is further defined by the subject of the shadow price γ_1, crop yield change, and per-hectare production. This condition requires farmers to balance the production costs of crops, the expected benefits from their cropping decisions, and the predicted yield variations resulting from climate change.

$$\frac{\partial L}{\partial Land_{ip}} = -\alpha_{ip}\left(Land_{ip}\right) - \gamma_2 \tag{7}$$

$$\frac{\partial L}{\partial Processcost_{inp}} = -CroppingD_{inp} - \gamma_3 \tag{8}$$

$$\frac{\partial L}{\partial Emioutput_{gip}} = Emiprice_g - \gamma_4 \tag{9}$$

Equation (7) shows that the value of cropland should be equal to the land rent associated with that specific usage. Equation (8) specifies the optimal use of inputs across various processing and production stages. It indicates that the optimal use of input occurs when the marginal benefit from using an additional unit of input equals the cost of operating a marginal unit. Equation (9) indicates that the emission has a societal cost, implying that biofuel production is feasible.

Study setup, model validation, and data source. Because biofuel is produced to replace gasoline and biofuel reduces emissions that have a value, we simulate Taiwan's biofuel production under several gasoline and emissions prices to determine how biofuel penetrates the gasoline market. Subsequently, we incorporate climate projections to explore how climate impacts on crop yields alter production patterns and to examine the extent of those impacts. The biofuel feedstock examined by this study is sweet potatoes, whose per-hectare yield and carbohydrate content are high and are under consideration by the government.

The per-litre gasoline price is based on the historical market price range of USD 0.674, 1.011, and 1.348. The emission price to be simulated ranges from USD 1 per tonne to USD 50 per tonne, with an increment of USD 1 per tonne. Therefore, 150 scenarios (3 gasoline prices × 50 emission prices) under different market conditions allow us to examine how market power affects biofuel production. Four Representative Concentration Pathways (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) are incorporated to evaluate the potential yield change and then re-simulate biofuel production. Before employing this model, we validate its usefulness by comparing the base simulation results and the observed data. Based on the 2010–2020 data released by the Taiwan Council of Agriculture (2021), we find that the simulated results slightly deviate from the observations. Since it is not expected to model an entire sectoral activity perfectly, this mathematical programming model can be considered adequate for conducting this biofuel study. The results are presented in Table 1.

RESULTS AND DISCUSSION

Visualisation of climate impacts

Figure 2 shows the impacts of climate change on Taiwan's precipitation and temperature. The RCP2.6 scenario assumes the world has substantial control over emissions (a nearly carbon-neutral scenario), with an expected temperature increase of 1 °C by 2100. The RCP8.5 scenario assumes countries did not control emissions, and the expected temperature increase may exceed 4 °C by 2100. The RCP4.5 scenario implies that policies and regulations are in place to control emissions. In contrast, the RCP6.0 scenario suggests that governments set only an upper bound on total emissions, without accounting for emission reductions. Table 2 shows the parameters of climate projections.

While most regions become warmer and more humid, the impacts on those regions could be highly diverse, especially for farmers' cropping decisions. Thus, potential fluctuations in biofuel production and emission reductions may be caused by climate-induced impacts on crop yields; we first need to estimate the effects on the upstream agricultural sector. This study updates Chang et al.'s (2011) data by AR5 to show how crop yields may be affected. We show that, under moderate climate change scenarios such as RCP2.6 and RCP4.5, crop yield changes are also relatively mild. However, when climate impacts are significant, as in the RCP6.0 or RCP8.5 scenarios, a more substantial yield change would result.

Table 3 is fundamental but essential to this study because it provides a basis for the model input. If crop yield is altered, the profit-maximising farmers would change their cropping decisions, and thus the pattern of biomass supply would deviate from the experience. A slight change in their cultivation practices could lead

Table 1. Model validation

Products	Production (t)		Price (USD/kg)	
	observation	deviation (%)	observation	deviation (%)
Rice	1 333 018	0.32	0.89	3.46
Corn	167 908	1.94	0.17	–0.18
Peanut	58 066	–19.56	1.14	–7.16
Hog	864 792	–0.19	2.72	–1.13
Broiler chicken	304 354	3.87	1.82	1.47
Native chicken	266 161	1.36	2.80	0.64
Egg	7 018 647	–0.28	5.00*	0.01

*Price per 100 eggs

Source: Authors' own elaboration

Figure 2. Change in Taiwan's precipitation and temperature under various representative concentration pathways (RCPs)

Source: Authors' own elaboration

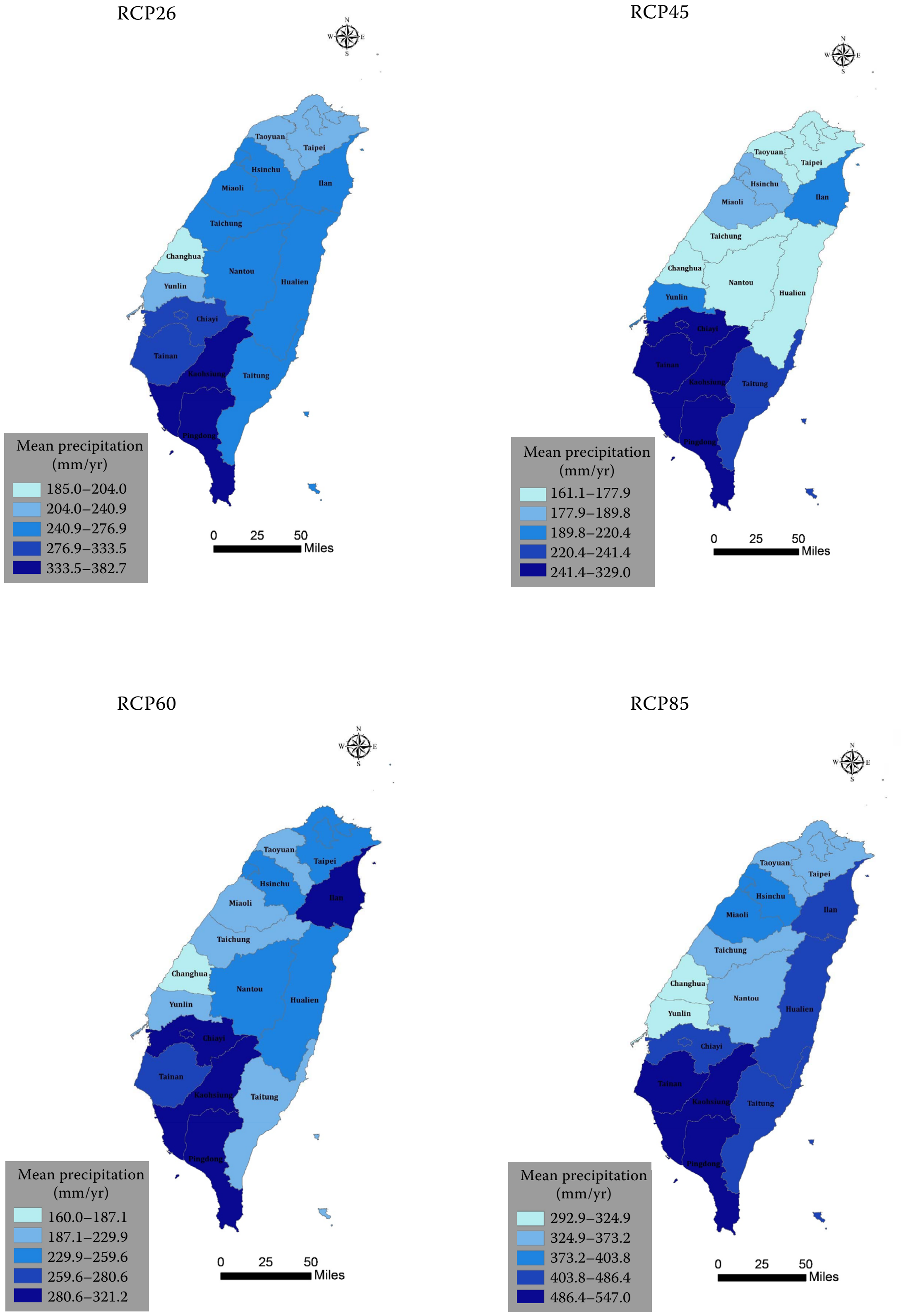
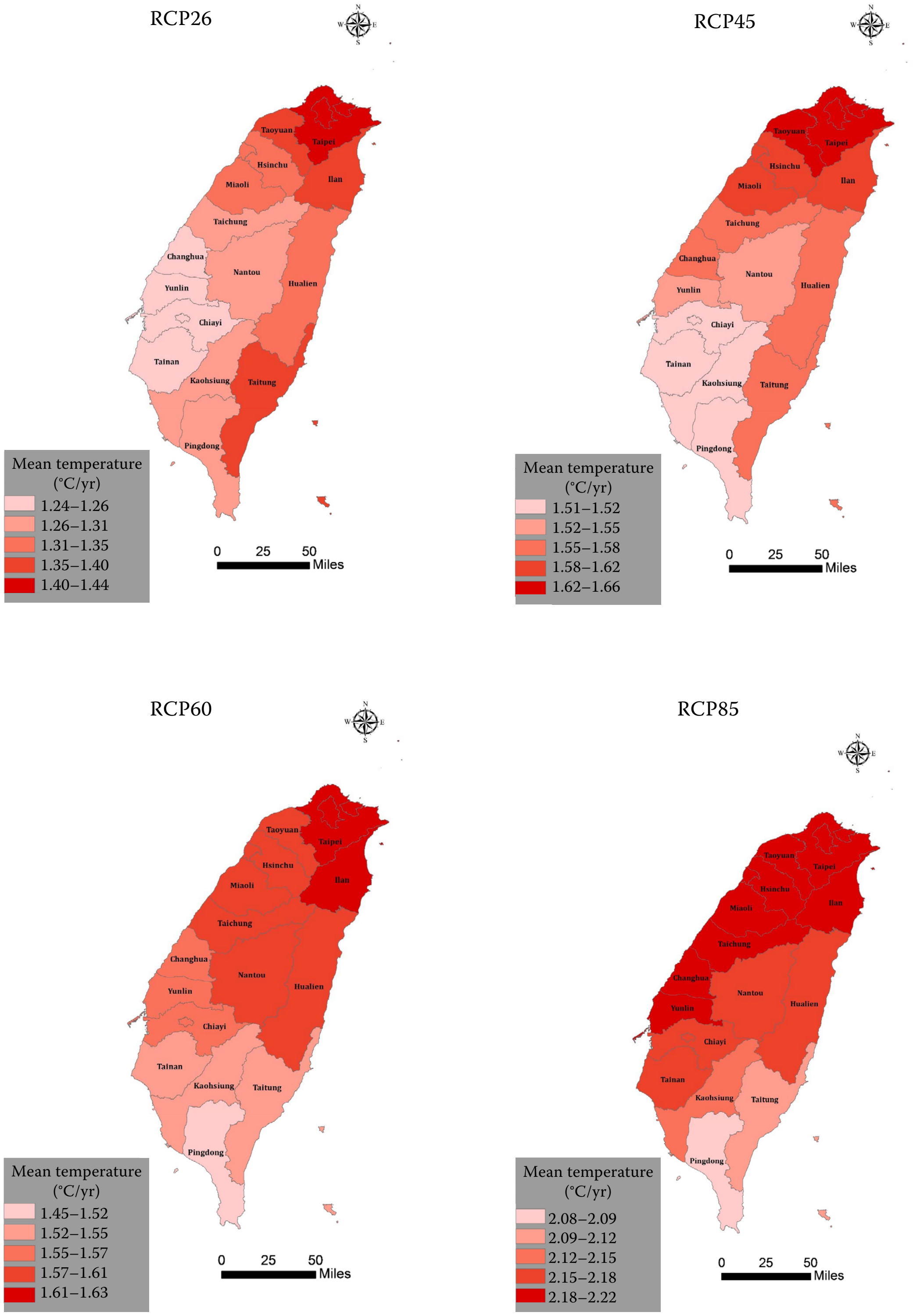


Figure 2 To be continued



to a significant shift in cropping patterns, destabilising the biofuel industry. Therefore, it is necessary to incorporate these climate scenarios to simulate potential market equilibria in both agricultural and biofuel markets.

Bioenergy production

In this section, we will elaborate on net biofuel production and discuss possible factors affecting Taiwan's biofuel development, including changes in land and

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Table 2. Climate data of different climate projections

	HADCM			
	A2		B2	
Temperature (%)	1		6	
Precipitation (%)	6		9	
	AR5			
	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Max temperature (°C)	1.78	1.56	1.36	1.54
Min temperature (°C)	0.40	0.44	0.24	0.43
Max precipitation (mm/day)	1.42	1.64	1.92	1.78
Min precipitation (mm/day)	–0.71	–1.05	–0.85	–0.72

HADCM A2 assumes a 1% increase in temperature with a 6% increase in precipitation, while projection B2 assumes a 6% increase in temperature with a 9% increase in rainfall.

HADCM – the climate projections of Hadley Centre Coupled Model; RCP – representative concentration pathways

Source: Authors' own elaboration

biomass use. Figure 3 illustrates the biofuel production under various RCPs. Past studies (Tso et al. 2009; Kung and Wu 2020) have analysed Taiwan's biofuel production and found that, in general, higher emission prices would benefit biofuel development because producers would gain more from emission sequestration. This study reveals a similar pattern, but with greater detail in the results when climate impacts are taken into account.

First, the results show that biofuel production follows the fundamental economic principle that a higher ethanol price would stimulate producers to produce more. However, since agricultural resources such as cropland, farm labour, and irrigation water are constrained, the upper bound is naturally defined, and changes in gasoline prices determine how quickly producers are willing to produce. The second result from Figure 3 indicates how biofuel production responds to the offset value. When the emission reduction becomes more valuable, the total biofuel production will expand from 450 million litres to about 580 million litres at a decreasing rate relative to the emission price, up to the resource constraint. However, because high gasoline prices have already stimulated biofuel production, and because the collection and transportation costs increase rapidly,

Table 3. Changes in crop yield under different representative concentration pathways (RCPs) (%)

Group	Products	RCP26	RCP45	RCP60	RCP85
Rice	rice	–1.83	–1.76	–1.90	–2.88
Cereal	corn	–3.30	–3.21	–3.45	–5.19
	wheat	0.17	0.08	0.12	0.24
	sorghum	19.42	19.07	20.44	30.64
Pulses	soybeans	4.86	2.62	3.59	6.96
	peanuts	0.76	1.08	1.03	1.30
	adzuki bean	–10.04	–11.02	–11.39	–16.22
Roots	sweet-potatoes	–3.77	–2.75	–3.29	–5.64
	potatoes	3.24	3.43	3.58	5.19
Special	tea	–2.29	–1.37	–1.79	–3.33
	cane for process	–0.84	–2.28	–1.92	–1.80
	cane for fresh	–0.84	–2.28	–1.92	–1.80
	sesame	–3.38	–5.92	–5.40	–6.18

Source: Authors' own elaboration (only major crops are presented)

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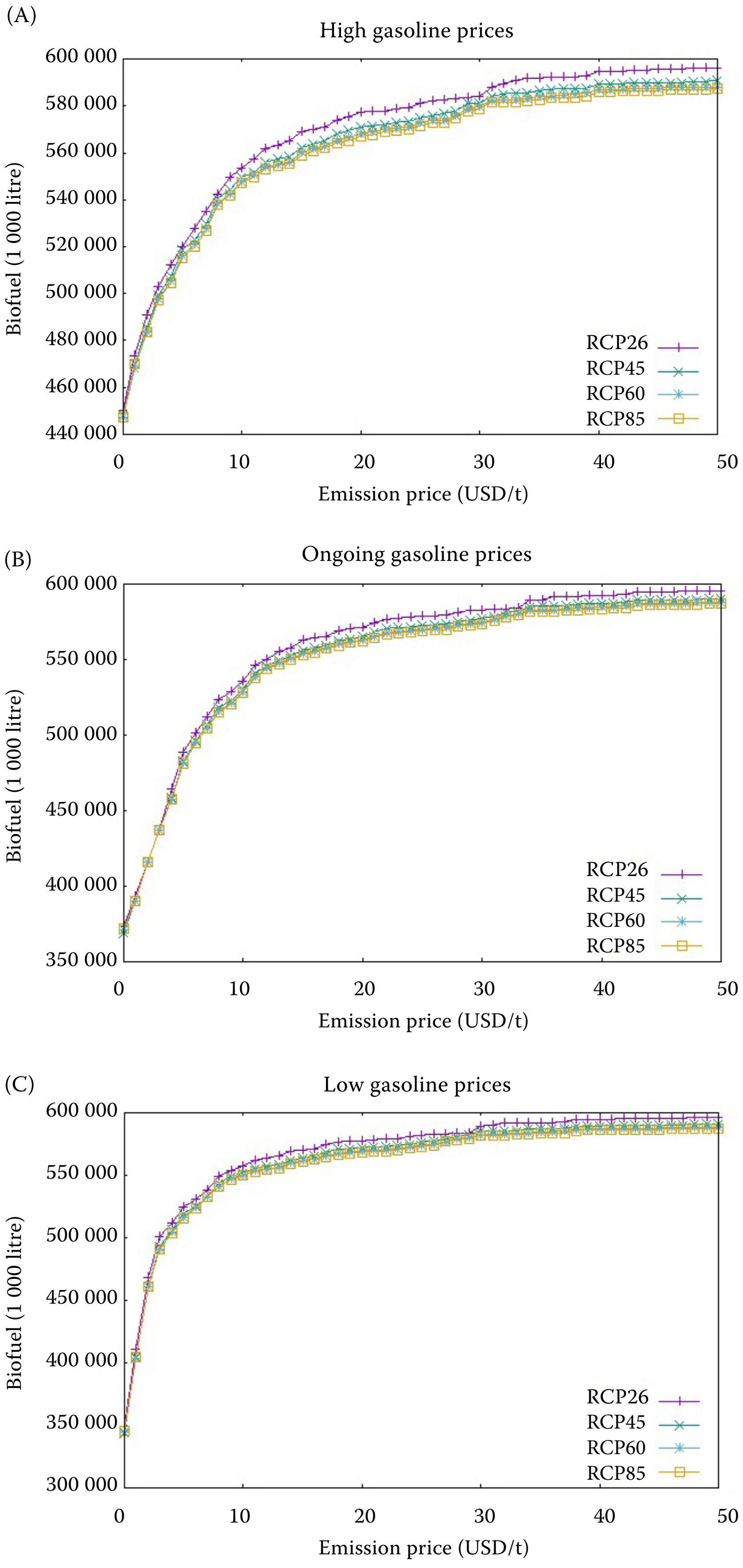

Figure 3. Biofuel production and input use change. (A) to (C) the biofuel production under different level of gasoline prices, (D) to (F) the input use change across climate change scenarios

RCP – representative concentration pathways

Source: Authors' own elaboration

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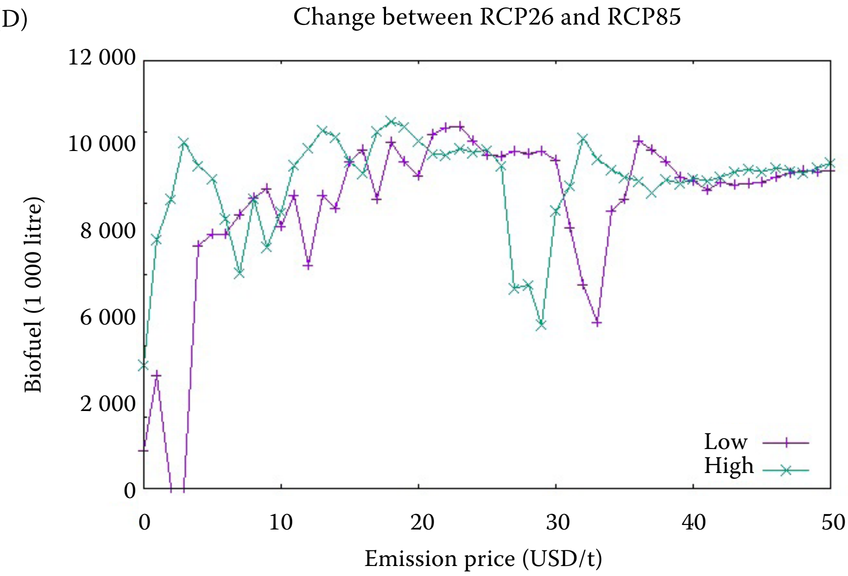
(D)



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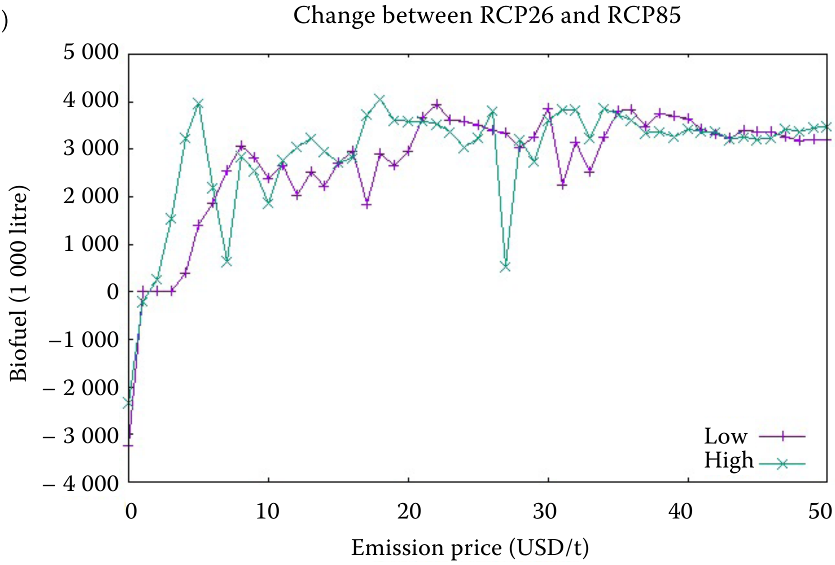

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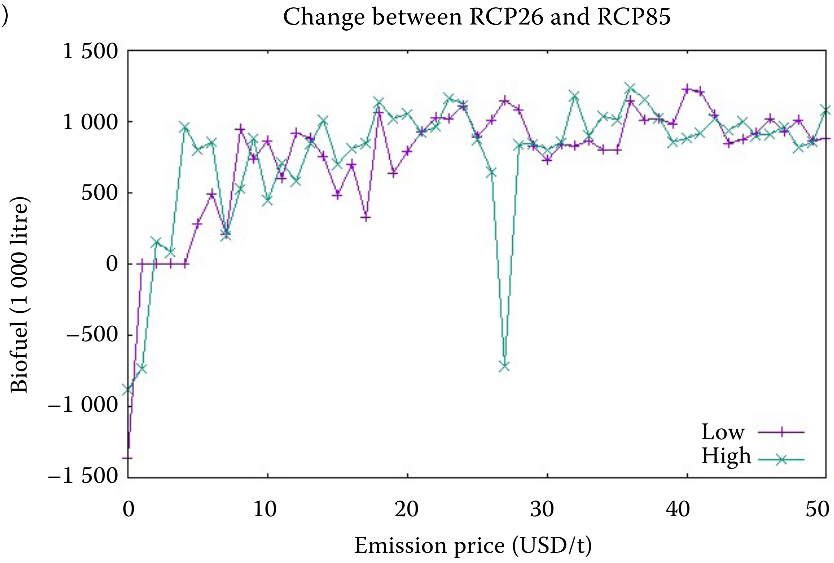

it would be more expensive to use additional biomass. Thus, the expansion of biofuel would grow at a lower rate than in low gasoline scenarios. Figures 3A–3C show this pattern.

Third, the results also indicate that as climate change becomes more severe, the total increase in biofuel production becomes more modest. For example, under the RCP8.5 scenario, total biofuel production would decrease by approximately 1.48% or 8.82 million litres [the y-axis ranges from 300 000–600 000 (thousand litres) in Figure 3A–3C, and thus 8 820 (thousand litres) is not significant in these figures]. This finding suggests that either the production strategy or cropping patterns may need to be adjusted, and it is essential to identify the causes of such variations to provide decision-makers and biofuel producers with informed insights. However, the results also indicate that while climate-induced yield changes affect total biofuel production, economic forces such as energy and emission prices can adjust production patterns and stabilise final output. Nevertheless, if a significant change in crop yield does not lead to a corresponding shift in biofuel production, the production pattern of agricultural commodities will likely vary. This adjustment to the cropping decision may incur some social costs, such as a significant land transfer.

Figure 3D–3F compares the net biofuel change under various climate change scenarios at different gasoline price levels, and these figures are the comparisons of lower emission scenarios (RCP26, RCP45, RCP60) to the highest emission scenario (RCP85). The results show that changes in biofuel production exhibit considerable fluctuations, and these variations are more pronounced when climate impacts are substantial. For example, Figure 3D compares biofuel production between RCP 2.6 and RCP 8.5, and the changes in biofuel production under different emission prices can be as significant as 10 million litres per year. However, Figure 3E and 3F show minor fluctuations in biofuel production, with the divergence in biofuel output generally ranging from –3 million to 3 million litres. Since we observe a sign of change in biofuel production, it implies a substantial shift in land-use and cropping decisions. This result provides insight by showing that further investigation is needed to identify the factors driving such a massive variation before we wholeheartedly accept the simple conclusion that higher gasoline and emission prices stimulate biofuel production.

Input use

To explore the factors driving changes in biofuel production and emission reductions, we first examine the total inputs used in biofuel production. Figure 4 shows that when emission reductions have no value, the biomass used for biofuel production ranges from 2.8 million to 3.6 million tonnes, depending on gasoline prices. However, biofuel production expands when the emission reductions are traded at nonzero prices. Thus, the use of biomass gradually increases to approximately 4.8 million tonnes, regardless of gasoline prices. This situation is reasonable because the cropland resource is limited, which naturally constrains the upper bound of biofuel production. Therefore, based on this result, we can further refine our previous conclusion: an increase in gasoline and emission prices would stimulate biofuel production and improve emission offset, but the extent of total production and offset capacity depends on the availability of land resources in the short term.

The results indicate that it is not necessary to maintain a high emission price to induce biofuel production for two reasons. First, the agricultural resources devoted to energy crops and biofuel production are highly constrained by the availability of cropland. However, producers would benefit from higher emission prices because the same amount of offset can be sold at a higher price in the emissions trading market. Second, gasoline prices are another direct factor driving up total biofuel production. If the government can enforce specific tax mechanisms to maintain a desired level of gasoline price, profit-maximising biofuel producers would exhaust available agricultural resources to achieve an efficient level of biofuel production.

Table 4 gives a more precise estimate of input use that may be used to assess investment and operating costs associated with the biofuel industry. For example, under RCP45 in the 'Low Gasoline Price' scenario, total biomass use would decline by approximately 1.66% from the base biomass use of 2.793 million tonnes.

Emission offset

Table 5 shows the total emission reductions from different scenarios. In general, the higher the emission price, the more CO_2 emissions can be offset through expanded biofuel production, and the higher the gasoline price, the greater the incentives are for biofuel producers to increase total biofuel production, thereby growing emission reductions. At a zero-emission price, the net emission reductions range from 38 448 to 50 421 tonnes. When the market assigns value to the emission, the net emission offset increases to approximately 66 736 tonnes. However, this pattern does not always follow these expectations, suggesting that

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something must have occurred during the simulation that is not well represented in the results. As shown in Figure 3, there is a need to determine the factor that leads to this situation. A possible explanation for this result is that there may be a substantial change in land use; thus, we need to verify the extent to which this change would occur.

Land use change

We demonstrate that climate change may have led to substantial changes in regional temperature and precipitation, and that land resource constraints limit total biofuel production. Therefore, it is necessary to investigate how climate impacts alter land productivity and how farmers adjust their cropping decisions in response to perceived environmental risks. From an economic viewpoint, farmers would plant the most profitable crops to maximise income rather than to maximise biofuel production. In other words, farmers' goal is not to provide the most biofuel feedstock but to make a profit. Thus, when climate change alters crop yields, farmers will consider this impact to maximise their expected profit during the harvest and marketing seasons.

Figure 5 shows the results of potential land-use change under different climate impacts, where Figure 5A indicates land transfer from cropland to land aside, and Figure 5B shows the opposite direction. Since crop yield is highly influenced by precipitation and temperature, altering these factors would inevitably affect crop output. Therefore, farmers whose land fertility has decreased and is expected to produce less than

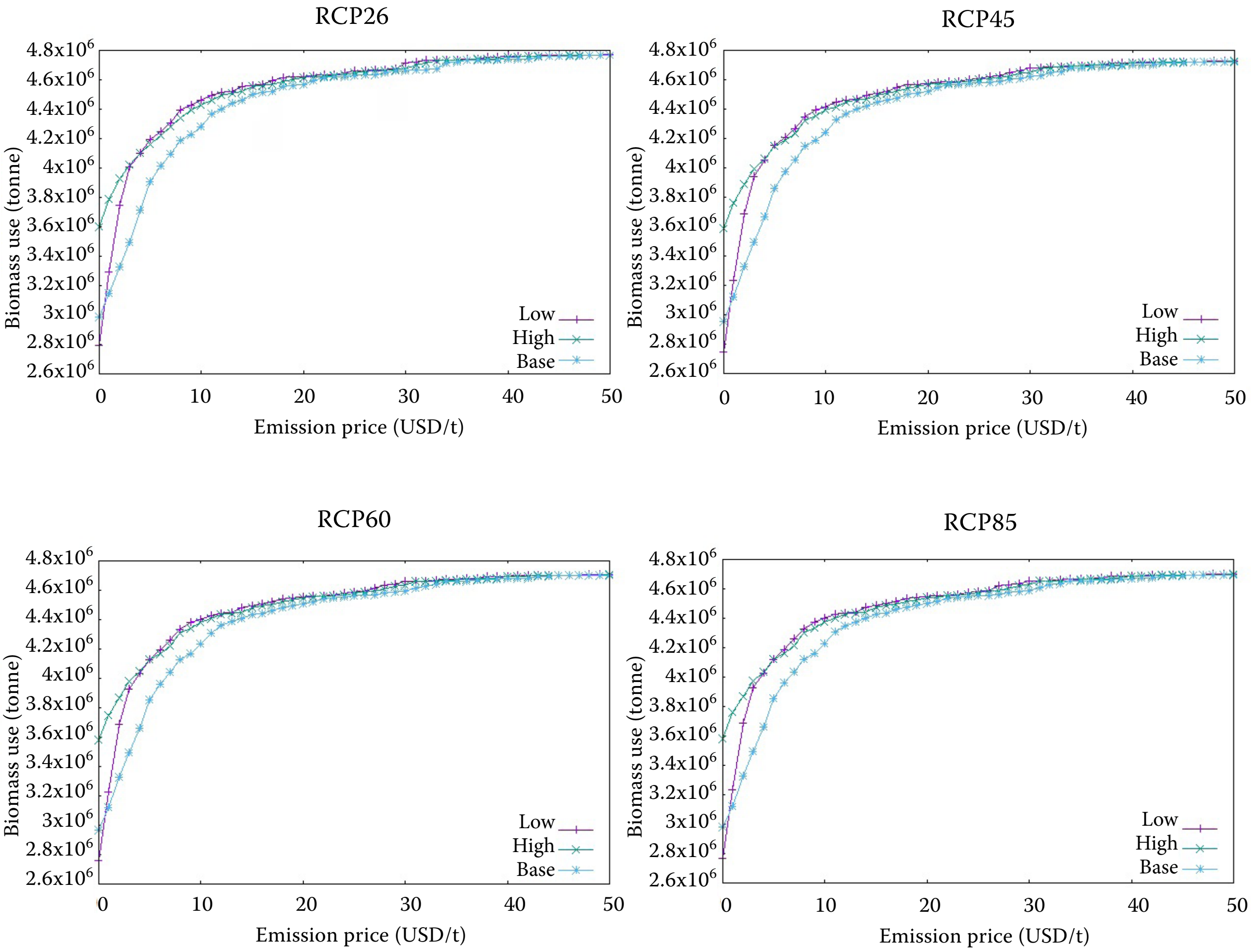

Figure 4. Input use at different gasoline price levels

RCP – representative concentration pathways
Source: Authors' own elaboration

Table 4. Input use changes under various representative concentration pathways (RCPs)

Emission price (USD/t)	RCP26 biomass use (t)	Low gasoline price (%)			High gasoline price (%)		
		RCP 45	RCP60	RCP85	RCP45	RCP60	RCP85
0	2 792 504	–1.66	–1.24	–0.98	28.44	28.11	28.11
1	3 289 835	–1.75	–1.87	–1.69	14.34	13.81	14.23
2	3 748 829	–1.68	–1.70	–1.73	3.62	3.20	3.20
3	4 004 877	–1.63	–1.92	–1.94	–0.28	–0.61	–0.73
4	4 098 214	–1.14	–1.58	–1.77	–0.98	–1.33	–1.51
5	4 193 140	–0.90	–1.51	–1.66	–1.12	–1.52	–1.70
6	4 248 246	–1.01	–1.26	–1.42	–1.51	–1.90	–2.08
7	4 307 815	–1.00	–1.08	–1.12	–1.66	–1.96	–2.18
8	4 392 020	–0.96	–1.38	–1.48	–1.59	–1.94	–2.04
9	4 428 841	–0.76	–1.06	–1.22	–1.70	–2.02	–2.17
10	4 459 352	–1.06	–1.31	–1.39	–1.43	–1.72	–1.86
11	4 497 400	–1.12	–1.48	–1.61	–1.89	–2.07	–2.20
12	4 511 975	–1.15	–1.58	–1.69	–1.43	–1.80	–1.93
13	4 522 274	–1.21	–1.63	–1.78	–1.38	–1.81	–1.90
14	4 551 990	–1.21	–1.56	–1.73	–1.86	–2.26	–2.41
15	4 561 404	–1.13	–1.48	–1.61	–1.43	–1.76	–1.95
16	4 569 944	–1.05	–1.41	–1.55	–1.33	–1.69	–1.82
17	4 595 019	–1.09	–1.59	–1.74	–1.61	–2.00	–2.15
18	4 615 314	–1.09	–1.59	–1.79	–1.57	–2.03	–2.19
19	4 619 903	–1.13	–1.58	–1.76	–1.41	–1.92	–2.10
20	4 622 384	–1.07	–1.51	–1.69	–1.21	–1.67	–1.84

Source: Authors' own elaboration

in the past from current cropping patterns would choose to set their land aside to avoid further loss. It is obvious that when a more significant environmental impact is encountered, more croplands will be set aside. About 14 000 to 25 000 hectares of cropland would be set aside, depending on the severity of the climate impacts.

However, climate change is also likely to turn some previously unprofitable land into profitable ones due to shifted temperature and precipitation patterns. Along with the economic incentives associated with selling biomass to biofuel producers, approximately 74 500 to 81 900 hectares of asideland currently return to production. In addition, the results indicate a decreasing trend in conversion, suggesting that farmers initially convert the most marginal land back into production. Nevertheless, because it is unlikely that society will be willing to forgive some crop species solely to maximise biofuel production (which is also not allowed in the model), the land conversion rate would remain relatively flat, even at high emission prices. These results also implicitly indicate why biofuel production would be limited, even if land use were to change.

Table 5. Total emission reduction (t) under different prices and representative concentration pathways (RCPs)

Gasoline price	USD 0.674/L			USD 1.011/L			USD 1.348/L		
CO$_2$ price (t)	USD 0	USD 10	USD 50	USD 0	USD 10	USD 50	USD 0	USD 10	USD 50
RCP26	39 095	62 431	66 804	50 421	62 008	66 761	41 786	59 959	66 736
RCP45	38 448	61 772	66 170	50 214	61 535	66 157	41 303	59 405	66 098
RCP60	38 611	61 612	65 902	50 086	61 358	65 867	41 515	59 233	65 838
RCP85	38 710	61 562	65 781	50 086	61 267	65 773	41 667	59 136	65 739

Source: Authors' own elaboration

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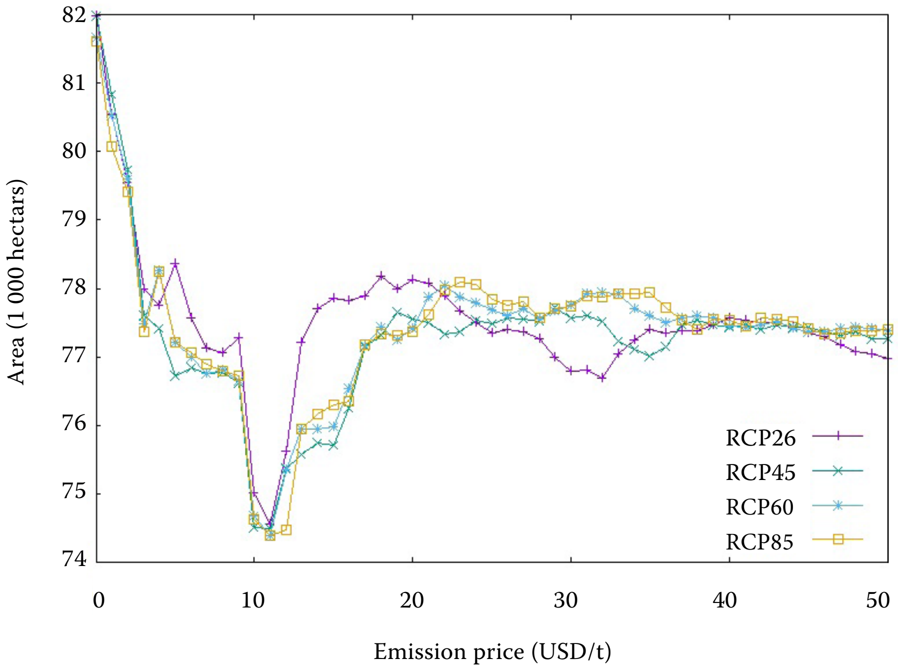
The results indicate that the shift in cropland use is likely the primary factor influencing total biofuel production and net emission reduction. However, in the long run, the constraint on the available cropland may be alleviated because farmers can further increase agricultural productivity by converting fallow land (i.e. currently abandoned cropland) back into use. Figure 6 shows this possibility.

The results indicate that such a conversion of fallow is not significant at low emission prices across all RCPs because the economic incentives from biofuel production and emission trading cannot cover the costs

(A) Aside land to cropland



(B) Cropland to aside land

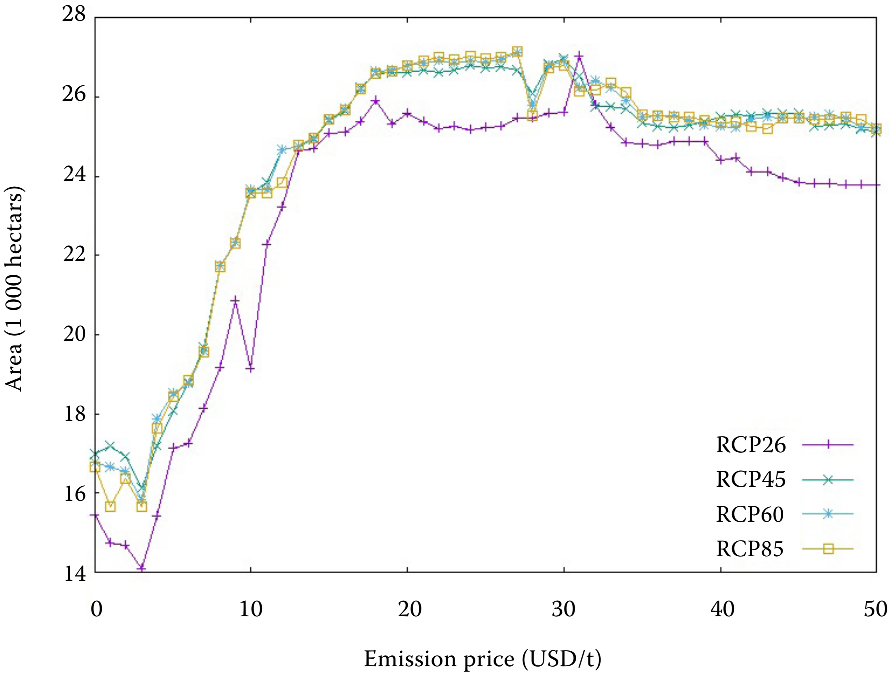


Figure 5. Change in cropland under representative concentration pathways (RCPs)

Source: Authors' own elaboration

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of discing, ploughing, planting, and harvesting crops. As the emission price increases, the benefits of replanting outweigh the costs, and thus, more fallow land may be returned to use. Nevertheless, this result only indicates that more currently abandoned land may be converted, but it does not explicitly show that all converted land must be planted with biofuel feedstocks. In the face of climate impacts, a reduction in crop yields would also stimulate farmers to cultivate more land to maintain their income streams.

Discussion

This study examines how changes in gasoline and emission prices may alter Taiwan's biofuel production and emission reduction. It also discusses how climate impacts would be involved and to what extent environmental risks affect land use and cropping patterns. Based on these results, some insightful policy recommendations could be made.

Reduce unnecessary bioenergy promotion policies. The results indicate that Taiwan's biofuel production could expand if producers receive sufficient economic incentives, even in the face of exogenous environmental risks that decrease per-hectare crop yields. Reichle (2023) shows that a properly designed emissions trading scheme can improve the profitability of green projects and thereby stimulate renewable energy production. Since Taiwan's biofuel production goal under the 'Renewable Energy Development Framework' is approximately 300 million litres, the emission price listed in the Emission Trading System (ETS) could be supportive.

There are many biofuel subsidies worldwide. For example, the United States offers a low-cost funding (up to USD 250 million and 50% of total project costs) to biofuel producers to expand biofuel production (USDA 2025) and the Indian government has offered capital subsidy for biofuel plants, tax benefits for biofuel materials and equipment, and low-interest loans

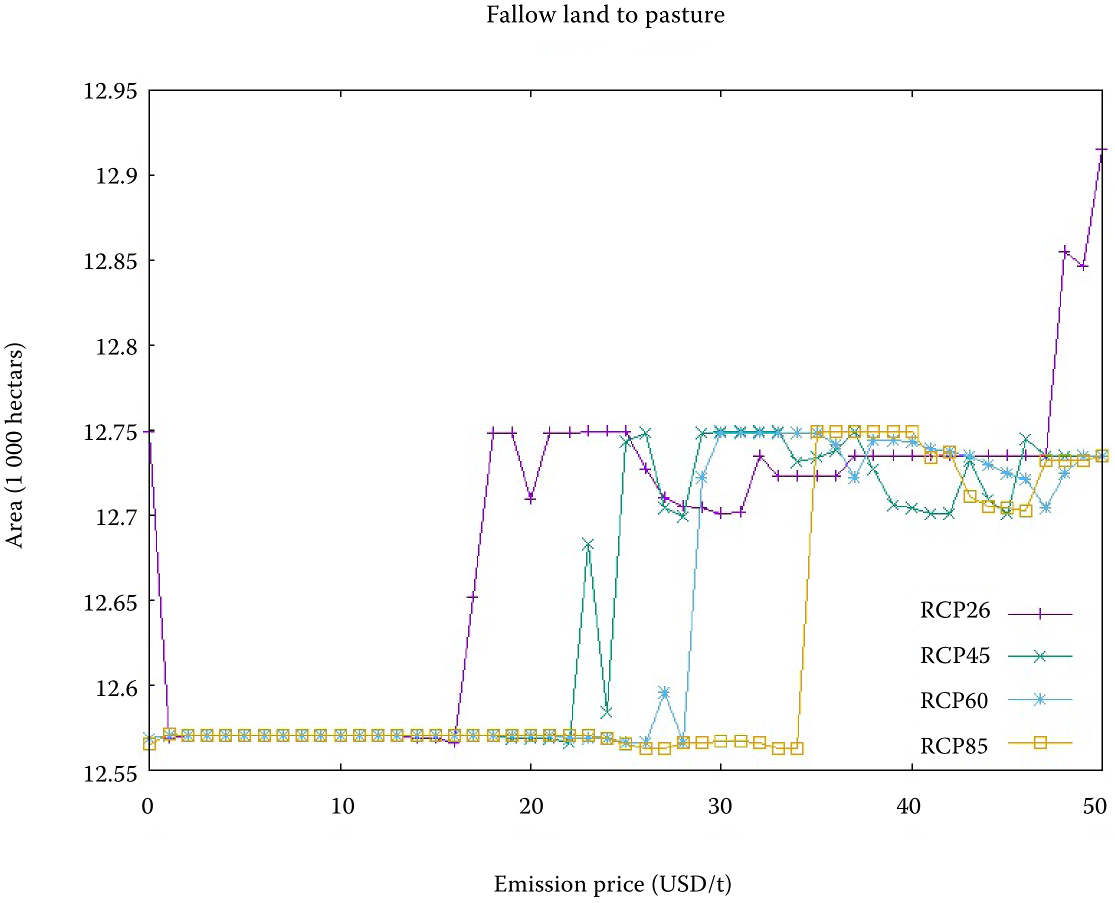

Figure 6. Change in non-cropland under representative concentration pathways (RCPs)

Source: Authors' own elaboration

to biofuel manufacturers (Ministry of New and Renewable Energy 2025). However, our results indicate that an efficient ETS that allows biofuel producers to realise offset value is sufficient to produce the required amount of biofuel. Since the results suggest that the upper bound of biofuel production exists, other promotional policies, such as price subsidies and tax cuts, offered to biofuel producers would not result in further expansion of biofuel production but would be a waste of capital.

Formulate a proper policy to sustain sustainable cropland use. We demonstrate that while biofuel can be produced at a desired level, land-use change could be substantial due to climate impacts and altered cropping decisions, which may subsequently affect the production and consumption of other agricultural commodities. For example, Khanna and Crago (2012) indicate that a potential land-use change may occur under large-scale biofuel production, and climate change may eventually have significant impacts on agricultural productivity (Syed et al. 2022). Additionally, Chang et al. (2011) note that sea-level rise driven by climate change may degrade soil quality in Taiwan; therefore, Taiwan's authority should not only focus on maximising biofuel production but also formulate policies to sustain food crop production, thereby improving food security. This situation may also be accompanied by other trade policies, such as maintaining minimum cropland requirements and adjusting import and export quotas.

Accommodation of cellulosic biofuel. This study uses sweet potato, which has a high energy conversion rate and per-hectare yield, as the primary biofuel feedstock. It shows that total biofuel production is sufficient under the E3 (3% biofuel and 97% gasoline) or E5 (5% biofuel and 95% gasoline) policies. However, the manufacturer is also developing vehicles compatible with higher biofuel use. The gas stations are also gradually replacing the oil pipelines and tanks with newer, more anti-corrosive ones. Thus, in the foreseeable future, Taiwan may implement a higher mandatory biofuel policy, such as an E10 or E15 fuel policy. A higher biofuel standard implies a further expansion of biofuel production. For example, pyrolysis is a cellulosic technology that can produce bio-oil (Cao et al. 2017). Because this advanced technology can consume large amounts of organic matter, it can greatly alleviate the food-to-energy concern commonly associated with conventional biofuel production. The application of cellulosic biofuel is more complex than that of traditional biofuels, and it will increase production costs. However, producers can recover part of their costs under an efficient ETS or profit when the emission price increases (Aui et al. 2021).

Promotion of green financing mechanisms. Biofuel development requires substantial capital investment to acquire land, build and operate plants, and collect and process biomass. Thus, developing the biofuel industry can be costly. Witcover and Williams (2020) estimate that per-gallon biofuel production could range from USD 3.25 to USD 4.0, and such a high cost would increase producers' operating risk. Over the past decade, the long-term interest rate in Taiwan was approximately 2.44%, and the firm's financing cost was not significant. The government would reimburse part of the costs in the form of tax cuts or output subsidies. However, as many countries have raised interest rates, the Central Bank of Taiwan has also raised its rates to reduce capital outflows. As of November 8, 2023, the long-term borrowing rate has climbed to more than 3.13%, substantially increasing the producer's financial costs. In addition, the Taiwanese government has launched numerous green projects, including green building, intelligent transportation, and resource recycling and utilisation, all of which require significant capital investment, implying that a reduction in biofuel subsidies would be expected. Many biofuel producers must seek alternative low-cost financing sources to sustain their operations and production.

CONCLUSION

This study revisits Taiwan's biofuel production profile, taking into account the latest climate reports. By formulating a stochastic, price-endogenous mathematical programming model, this study investigates how climate change affects crop yields, land use, and subsequent biofuel production and emission reductions. The results would provide more useful information to decision-makers and practitioners. The key findings of this study are summarised as follows:

First, as the ETS can effectively operate, allowing firms to trade emission offsets, the economic benefits of biofuel would increase, thereby driving up total biofuel production to 596 million litres and emission reductions to 66 700 tonnes. Second, climate change would indirectly affect total biofuel production by altering crop yields and farming decisions. Based on their price and cost expectations, the farmers will choose a cropping pattern that maximises their income. Third, a change in cropping patterns would subsequently alter current land use. About 14 000–25 000 hectares of cropland will be set idle because of a loss in production, while 74 500–81 900 hectares of idle land will be cultivated again. Additionally,

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to recover the lost production due to climate change, about 12 500 hectares of currently abandoned cropland will be converted back into use.

The challenges and limitations of this study also merit discussion. While climate change has altered regional temperatures and precipitation, it does not mean society will suffer from these changes. For example, increases in wheat, soybeans, and sorghum may offset decreases in rice and corn yields. In addition, the model does not specify the actions that biofuel producers and farmers should take; it simply indicates that the optimal allocation, which maximises social welfare, would be achieved given a set of crops, gasoline, and emission prices. A more detailed and specific analysis regarding income distributions among farmers may be necessary.

Data availability

The reference provides a data source, and the raw data is available upon request.

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