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Effects of Biofuel Crop Expansion on Green Gross Domestic Product

Piyanon Haputta [1,2,3], Thongchart Bowonthumrongchai [4], Nattapong Puttanapong [5] and Shabbir H. Gheewala [1,2,*]

[1] The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand; piyanonk@staff.tu.ac.th
[2] Centre of Excellence on Energy Technology and Environment (CEE), Ministry of Higher Education, Science, Research and Innovation, Bangkok 10400, Thailand
[3] Faculty of Science and Technology, Thammasat University, Pathum Thani 12120, Thailand
[4] Faculty of Economics, Srinakharinwirot University, Bangkok 10110, Thailand; thongchart@g.swu.ac.th
[5] Faculty of Economics, Thammasat University, Bangkok 10200, Thailand; nattapong@econ.tu.ac.th
* Correspondence: shabbir_g@jgsee.kmutt.ac.th; Tel.: +66-2-470-8309; Fax: +66-2-872-9805

Abstract: Following Thailand's Alternative Energy Development Plan, lands for sugarcane and oil palm are being expanded to support biofuel production, thus decreasing the availability of land for other crops. Not only does this lead to the change in Gross Domestic Product (GDP) but also environmental consequences. This study assessed the effects of land expansion caused by biofuel promotion on Green GDP, which is the conventional GDP after adjusting for environmental damage. A static computable general equilibrium (CGE) model combined with life cycle impact assessment was used to estimate the effects of land expansion on economic transactions and conventional GDP. Results showed that compared with the business-as-usual scenario, expanding land for biofuel crops increased the Green GDP. However, rice cultivation and milling were adversely affected by the substitution of biofuel crops. Furthermore, expanding biofuel crops slightly reduced the production capacity of some industrial sectors. The Green GDP for biofuel crop expansion policies was greatest when abandoned rice fields were utilized for agriculture and lowest when forests were transformed. Using CGE to investigate the effects of policy on Green GDP yielded results that were comprehensive for decision making. The method presented in this study can be utilized for future Green GDP research focusing on other biofuel productions.

Keywords: land expansion; biofuels; Green GDP; computable general equilibrium; life cycle impact assessment

Citation: Haputta, P.; Bowonthumrongchai, T.; Puttanapong, N.; Gheewala, S.H. Effects of Biofuel Crop Expansion on Green Gross Domestic Product. *Sustainability* **2022**, *14*, 3369. https://doi.org/10.3390/su14063369

Academic Editors: Nallapaneni Manoj Kumar, Md Ariful Haque and Sarif Patwary

Received: 11 February 2022
Accepted: 11 March 2022
Published: 13 March 2022

1. Introduction

Biofuels, e.g., ethanol from cane molasses and cassava and biodiesel from palm oil, have been promoted to replace gasoline and diesel in the transportation sector in Thailand to reduce the mounting greenhouse gas (GHG) emissions (The list of all abbreviations is shown in Abbreviations) from conventional fuel consumption. The Department of Alternative Energy Development and Efficiency (DEDE) reported that biofuel consumption increased continuously during 2008–2017 [1–3], as shown in Figure 1. Additionally, a decade before 2017, the domestic demand for ethanol was higher than the ethanol supply [4]. Therefore, ethanol exports were limited in the years following. Increasing ethanol production capability is thus still necessary to be able to support domestic and foreign demands.

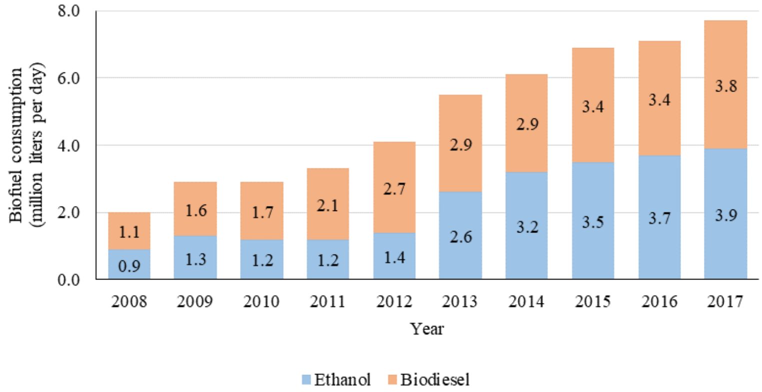

Figure 1. Thailand's biofuel consumption (million liters per day) [1–3].

However, the promotion of biofuels increases the demand for feedstock crops that in turn leads to the expansion of land dedicated to feedstock crops. Based on Thailand's Alternative Energy Development Plan (AEDP) 2015, lands for sugarcane and oil palm cultivation are being targeted to increase from 1.6 and 0.7 million ha in 2015 to 2.6 and 6.2 million ha in 2026, respectively (i.e., annually increased by 4.5 and 4.8 percent during 2015–2026) [5]. The expansion of land for feedstock crops can reduce the availability of land for other purposes, which then adversely affects economic opportunity for other activities. However, the economy-wide impact of land expansion induced by biofuel promotion is not found in any earlier studies, even though more than 40 percent of total land area is used by agriculture and the agricultural sector contributes approximately 10 percent to the Gross Domestic Product (GDP).

The measurement of the economy-wide effects of land expansion can be presented through GDP, as several earlier studies have shown. Despite ignoring the effects of land expansion, Silalertruksa and Gheewala [6] used GDP as an indicator to present the economic impact of bioethanol production in Thailand. Wianwiwat and Asafu-Adjaye [7], Kaenchan et al. [8], Phomsoda et al. [9], and Phomsoda et al. [10] revealed the dynamic effects of biofuel promotion on the economy through the intertemporal change in real GDP. However, although GDP is a standard measure for economic growth, it does not reflect actual human well-being as it does not account for social sustainability and future environmental consequences of present consumption [11,12]. Thus, Green GDP and other similar indices for sustainable development such as the Index of Sustainable Economic Welfare (ISWE) and the Genuine Progress Indicator (GPI) were developed to fill this lack [12,13].

Green GDP is an index of sustainable economic growth where the degradation and depletion of environmental and natural resources are subtracted from the conventional GDP. Since environmental and natural resources can be considered as the stocks of production factors used for generating the GDP of a country, their degradation and depletion should be deducted from the conventional GDP to derive the remaining stocks for the future. Green GDP has widely been adopted to promote more sustainable practices in several studies. For example, Li and Fang [14] presented Green GDP of all countries by integrating the total GDP with ecosystem services values obtained from spatial analysis based on Geographic Information System (GIS). Stjepanović et al. [15] measured Green GDP across countries by capturing emission, waste, and natural resource depletion. In addition, by incorporating greenhouse gas emissions, Kunanuntakij et al. [16] estimated Thailand's green GDP by using economic input–output life cycle assessment.

This study aimed to assess the effects of biofuel crop expansion on Thailand's Green GDP to address the lack of studies on the economy-wide effects of biofuel crop expansion that can in turn support policymakers in making decisions toward sustainable biofuel development in Thailand. The expansion of biofuel crops was incorporated relying on the targets officially published in AEDP 2015. Three scenarios of land expansion alternatives were considered in this study. In addition, the impacts of environmental interventions, i.e., air emissions, land transformation, water consumption, and fossil consumption, were captured.

2. Methods

Green GDP is defined as the *Conventional GDP* subtracted by the cost of environmental degradation and natural resource depletion, where environmental degradation refers to the effects of GHG emissions and land use and natural resource depletion denotes the depletion of water and fossil resources. The calculation of *Green GDP* is summarized in Equations (1) and (2), where *TEC* is the total environmental cost, *COP* is the cost of pollution (GHGs), *COL* is the cost of land degradation, *CWD* is the cost of water depletion, and *CFD* is the cost of fossil depletion.

$$Green\ GDP = Conventional\ GDP - TEC \tag{1}$$

$$TEC = COP + COL + CWD + CFD \tag{2}$$

The effects of biofuel crop expansion on *Green GDP* were estimated by comparing the business-as-usual (BAU) scenario with that in which biofuel crop expansion occurs. *Conventional GDP* was estimated using a static computable general equilibrium (CGE) model, a macroeconomic model for assessing the economy-wide impacts of policies that can also be modified to incorporate the environmental impacts of policies [8]. The procedure to formulate the CGE model used in this study is described in Section 2.1. The modification of the model to incorporate widespread environmental effects is presented in Section 2.2. The methods and equations for assessing the cost of environmental degradation and natural resource depletion are presented in Section 2.2.

2.1. CGE Model Setup

The standard CGE model developed by the Partnership for Economic Policy (PEP) research network [17] was used in the present study to estimate the effects of biofuel crop expansion. Model setup and simulation scenarios are detailed in the following subsections.

2.1.1. Model Description

Following the conventional structure of general equilibrium simulation, the model included four main economic agents: the production sectors, the aggregated household, the government, and the rest of the world. Main connectivities of transactions and activities are depicted in Figure 2. The consumption behavior of a household is governed by the Stone–Geary utility maximization framework, allowing for optimal adjustment of the consumption basket under the budget constraint. As illustrated in Figure 3, all production activities were structured based on the 4-level nested hierarchy, enabling the flexibility of selecting the optimal proportion of inputs and factors of production. In particular, the first level of this structure followed the Leontief production function, imposing the fixed ratio of value-added and total intermediate input. The second layer determined the distribution of value-added components and the selection of intermediate inputs. In the case of value-added allocation, a constant elasticity of substitution (CES) specification governed the optimal combination of labor and capital-land composite. For the total intermediate input, the selection was based on the Leontief production function, constantly demanding intermediate inputs by using a fixed proportion. In the third layer, the CES framework optimized the combination of land and capital. Considered one of the key features of this model, the last layer enriched the details of demand for land by specifically identifying the classification of land use into three categories: agricultural land, forest, and abandoned rice field.

Following the standard specification of CGE model, the CES mechanism determined the optimal composite of import and domestically produced goods. Similarly, a constant elasticity of transformation (CET) optimized the export decision, weighting the proportion of domestic sales and exports.

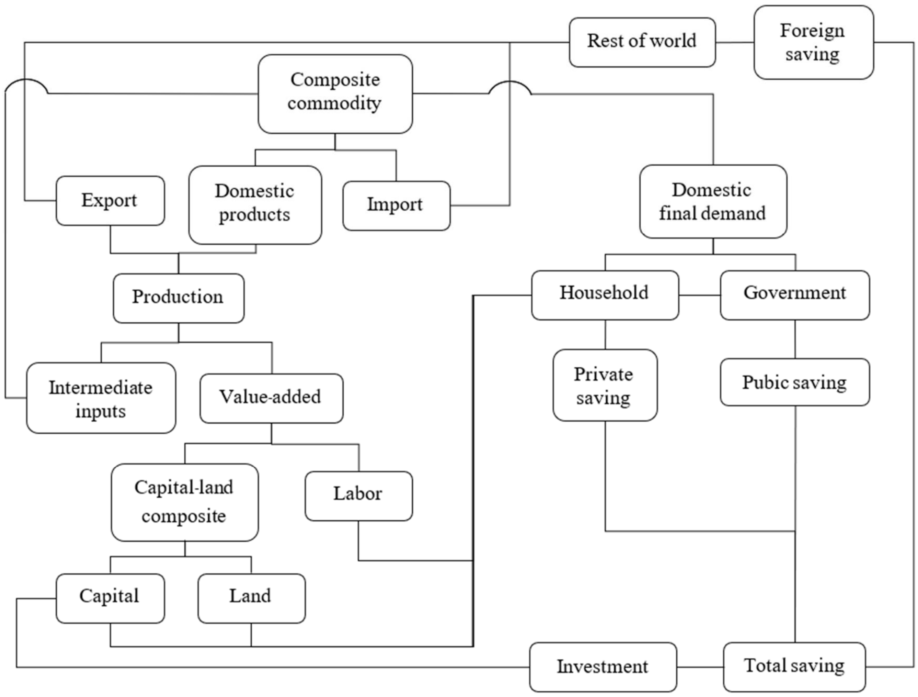

Figure 2. Main connectivities of economic transactions and activities within the CGE model.

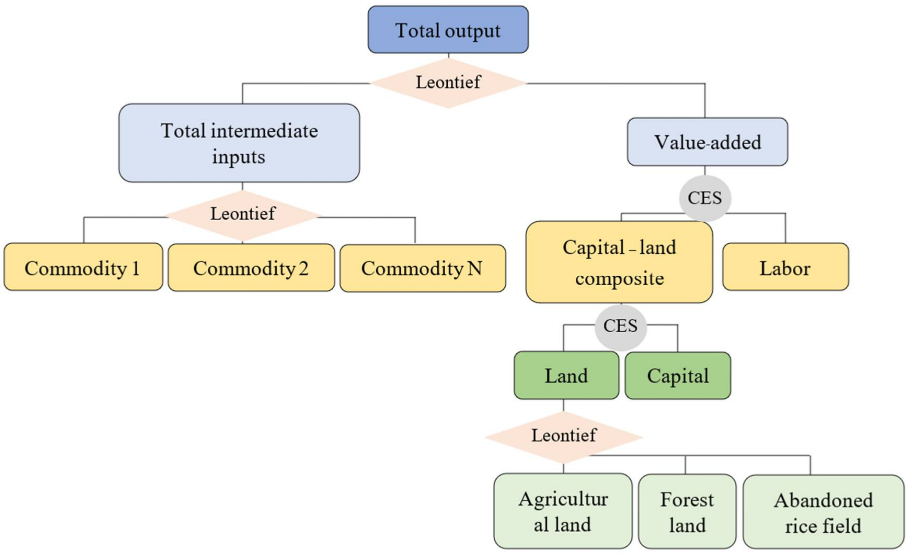

Figure 3. Structure of production.

2.1.2. Model Closure

To equalize the number of endogenous variables and equations, some variables were assigned to be exogenous. Following the conventional criteria introduced by Decaluwé et al. [17], variables influenced by the global economy and those determined by policymakers were specified as being exogenous. Thus, the international prices of imported and exported products, the current account balance, and the exchange rate were determined exogenously. Likewise, the policy-determined exogenous variables were government expenditure, domestic wage, capital demand, total investment, and the tax rate. Since the minimum requirements for foods and necessary goods are the primary demand for humans, the minimum consumption of a household was also specified exogenously.

Because the flexible adjustment of the biofuel crop sector was one of the main features of this model, the demand for the capital of biofuel crop plantation was endogenously determined to enable unconstrained variation in the nested structure of biofuel crop production. Also, this specification allowed the model to perform simulation scenarios by assigning the output of a specific biofuel crop exogenously.

2.1.3. Database

Similar to the conventional specification of the CGE model, the Social Accounting Matrix (SAM) was a primary source of data [18]. The SAM used in this research has been constructed based on the 2015 input–output (IO) table and officially produced and publicly distributed by Thailand's Office of the National Economic and Social Development Council [19].

The constructed SAM contained 39 production sectors, compromising between the mathematically solvable property of the model and obtaining sufficient detail for environmental and economic analysis. The SAM also included the main economic agents which are the government, the aggregated representative of households, and the rest of the world. The details of production sectors are exhibited in Appendix A, Table A1. To conform to the standard initialization of the model, elasticity parameters were obtained from Decaluwé et al. [17] and OECD/ILO [20] (Appendix A, Table A2). In accordance with the most recent published data of land use, pollution, and environmental indicators, the SAM and all variables of this CGE model were calibrated to the base year of 2017. Specifically, the calibration of SAM followed the steps introduced in Serag et al. [21]. The macroeconomic data were obtained from the official database of national income published by NESDC. Regularly produced and distributed by Thailand's National Statistical Office (NSO), details of production activities were obtained from the official industrial census and household consumption statistics were derived from the official socioeconomic survey. The compilation of data used the cross-entropy estimation technique as introduced by Robinson et al. [22].

2.1.4. Simulation Scenarios

Biofuel crop expansion has three simulation scenarios. Among them, the percent increment of biofuel crops was identically defined on the basis of the annual targets in AEDP 2015 [5]. That is, the output of cassava, sugarcane, and oil palm increased by 6.2, 4.5, and 3.7 percent, respectively. The output of sugarcane and oil palm production increased by expanding land while the output of cassava production increased due to productivity improvement in all scenarios.

- S1: There is no transformation of forest area to cropland. Thus, the total dimension of agricultural land is constant, and the expansion of sugarcane and oil palm can diminish the size of other croplands.
- S2: Forest area (0.02 percent) is assumed to be transformed to agricultural land following the average annual decreasing rate of forest area during 2014–2016 [23]. Therefore, in this scenario, more agricultural land is available.
- S3: Abandoned rice fields (164,800 ha [24]) are utilized by transforming to agricultural land. Therefore, more agricultural land is available.

2.2. Expanding the Model to Capture Environmental Impacts

This study considered the environmental impacts caused by air emissions, land transformation, water consumption, and fossil resource consumption. Thus, the CGE model was expanded to capture these features and estimate the environmental impacts of scenarios S1–S3.

2.2.1. Air Emissions

This study focused on global warming [presented in a unit of kg carbon dioxide equivalent (kg CO_2 eq.)] caused by greenhouse gas (GHG) emissions. In particular, the standard CGE model was modified to incorporate the conversion factors, enabling the computation of CO_2 emissions from energy consumption and chemical fertilizer use.

The CO_2 conversion factors for energy consumption are shown in Table 1. As the sectoral production and commodity consumption in the CGE model are conventionally represented in monetary units, Table 1 exhibits all price factors (PEs) applied to convert the values of energy consumption into the physical base quantity unit. Conversion factors of CO_2 emissions are not applied in the use of crude oil and natural gas in the chemical industry and petroleum refineries and the use of petroleum products in the chemical industry because they are used as raw materials (feedstock) and not burned in these sectors. The conversion factors for CO_2 emissions from chemical fertilizer use (EFAG) were calculated by dividing the total CO_2 emissions from chemical fertilizer use of approximately 5547 million tonnes CO_2 eq. in 2015 by the total value of chemical fertilizer use of the whole nation in 2015 (derived from the SAM table). The 5547 million tonnes CO_2 eq. was derived based on the information on chemical fertilizer imports from the Office of Agricultural Economics [25] and the methods to calculate CO_2 emissions and emission factors of chemical fertilizer production and use given by the Thailand Greenhouse Gas Management Organization [26].

Table 1. CO_2 conversion factors for energy consumption.

Sources of Energy	EFEC (1000 Tonnes CO_2/ktoe) [a]	PE (1000 Million THB/ktoe) [b]
Coal and lignite	4.10533	0.004
Crude oil and natural gas	1.03978	0.016
Petroleum products	2.48847	0.053

Notes: [a] is CO_2 emission factors calculated from dividing the total emissions from each energy classification in 2015 [27] by its consumption amount in 2015 [28]; [b] is a ratio of the total emissions from each energy classification in 2015 per the total value of the corresponding energy consumption in 2015 (derived from the SAM table); ktoe is 1000 tonnes of oil equivalent; and THB is Thai baht.

The CO_2 conversion factors for energy consumption and chemical fertilizer use were attached to the database of the model. This study included Equations (3)–(7), modified from Kaenchan et al. [8], to compute the total CO_2 emissions.

The total amount of CO_2 emitted from each production sector can be estimated as shown in Equations (3)–(5), where $ECCO_{i,j}$ is the CO_2 emission caused by the consumption of energy product i by production sector j; $DI_{i,j}$ denotes the use of intermediate product i by production sector j; $EFEC_i$ is the emission coefficient corresponding to the consumption of product i; PE_i indicates the price of energy product i; $AGCO_{chem,jagri}$ represents the total amount of CO_2 emitted by the utilization of chemical fertilizer in farming activity j_{agri}; $DI_{chem,jagri}$ identifies the use of chemical fertilizer in farming activity j_{agri}; $EFAG_{chem,jagri}$ is the emission coefficient of using chemical fertilizer in farming activity j_{agri}, and $INTCO_j$ is the amount of CO_2 emitted by a production activity of sector j.

$$ECCO_{i,j} = \frac{DI_{i,j} \times EFEC_i}{PE_j} \tag{3}$$

$$AGCO_{chem,j_{agri}} = DI_{chem,j_{agri}} \times EFAG_{chem,j_{agri}} \tag{4}$$

$$INTCO_j = \sum_i ECCO_{i,j} + \sum_{chem} AGCO_{chem,j_{agri}} \tag{5}$$

Equation (6) specifies the computation of the total amount of CO_2 emitted by final consumption, where $FNCO_i$ is the emission caused by consumption of product i by household, government, and investment; $C_{i,h}$ denotes consumption made by household h of product i; I_i represents the investment-oriented deployment of goods i; and G_i indicates the governmental utilization of product i.

$$FNCO_i = \frac{(\sum_h C_{i,h} + I_i + G_i) \times EFEC_i}{PE_i} \tag{6}$$

Equation (7) mathematically identifies the total CO_2 emission, where TCO represents the sum of CO_2 emission constituted by intermediate utilization ($INTCO_j$) and final consumption ($FNCO_i$).

$$TCO = \sum_j INTCO_j + \sum_i FNCO_i \tag{7}$$

2.2.2. Land Transformation

Land is included in capital in the standard CGE model developed by the PEP research network [17]. As land plays an important role in the determined scenarios, it was separated from capital in this study, as shown in Figure 3. The land use of each agricultural subsector and its rental rate that is presented in Table 2 were employed to separate land from capital. The information on land use and the rental rate of land types in 2015 was mainly provided by OAE [29,30]. Only the area of livestock and forestry that are not provided by OAE were from Thailand's Land Development Department [24].

Table 2. Cropland and rental rate by agricultural subsector.

Land Use Types	2015 Land Use (ha) [a]	2015 Rental Rate (THB/ha) [b]
Paddy	10,643,878	5011
Maize	1,053,935	5072
Tapioca	1,491,155	6248
Sugarcane	1,534,632	8351
Oil palm	813,296	6031
Livestock	306,619	6222
Forestry	16,935,417	62
Other agricultures	7,606,344	6222

Notes: Rental rate of the land dedicated to livestock and other agricultures is assumed to be equivalent to the average rental rate of the first five land use types. As forest land has no rent, the rental rate for forestry is assumed to be 1 percent of the average rental rate of the first five land use types to enable model simulation. This assumption does not affect the results because relative prices are relied on in the model.

The effects of biofuel crop expansion (in each simulation scenario) on land transformation could be estimated by comparing the size of each land use type in the simulation scenario with that of the BAU. Equations (8) and (9) were used to calculate the size of land use types in the simulation scenarios. Mathematically, $Qland_j$ denotes the size of the land used by sector j (ha); a_qland_j is the coefficient for land use of sector j; $KNDC_j$ refers to the demand for land of sector j (Thai baht or THB); $QlandO_j$ is the initial size of the land used by sector j (ha; i.e., [a] in Table 2); and $KNDO_j$ is the initial value of the demand for land of sector j (THB; i.e., the product of [a] and [b] in Table 2).

$$Qland_j = a\_qland_j \times KNDC_j \tag{8}$$

$$a\_qland_j = \frac{QlandO_j}{KNDO_j} \tag{9}$$

Not only does land transformation decrease the number of species on land but it also contributes indirectly to global warming from burning and losing the ability to absorb carbon dioxide.

The impact of land transformation on the number of species could be estimated using the endpoint characterization factors for land transformation from Goedkoop et al. [31]. Following their computational technique, transforming one agricultural land to another one had no impact to the number of species, only the transformation of forest to agricultural land has. Further explanation on assessing the impact of land transformation on species loss can be found in Section 2.2.4.

Considering the impacts of land transformation on global warming, this study followed the method introduced by Silalertruksa and Gheewala [32] to compute GHG emissions that are caused by land transformation. The method is summarized in Equation (10), where *EFLUC* is the GHG emission factor for land transformation (tonne CO_2 eq./ha.yr); *BCL* stands for biomass carbon stock loss (the loss of the aboveground biomass carbon stock in the transformed land); *CSOC* is the change in soil carbon stock (i.e., the difference between soil organic carbon of the land before transformation (SOC_{before}) and soil organic carbon of the land after transformation (SOC_{after}), as shown in Equation (11)); *GHGLUC* is the amount of GHG emissions from land clearing (i.e., the sum of CO_2 *emissions* and *non-*CO_2 *GHG emissions* caused by burning biomass in the transformed land as presented in Equation (12)); and *T* refers to the time span of crop. The factor of 3.664 in Equation (10) was applied to convert carbon (12.01) to CO_2 (44.01). The information used for the calculation of Equations (10)–(12) is presented in Appendix A, Table A3.

$$EFLUC = \left(\frac{BCL \times 3.664}{T}\right) + \left(\frac{CSOC \times 3.664}{T}\right) + \left(\frac{GHGLUC}{T}\right) \quad (10)$$

$$CSOC = SOC_{before} - SOC_{after} \quad (11)$$

$$GHGLUC = CO_2 emissions + Non - CO_2 GHGemissions \quad (12)$$

Referring to Section 2.1.4, the two types of land being transformed were the forest (scenario S2) and abandoned rice field (scenario S3). The transformation of one type of agricultural land to another type of agricultural land in scenario S1 was considered to have no change in GHG emissions. The transformation of the forest in scenario S2 is based on the assumption that 50 percent of the 0.02 percent of Thailand's forest area in 2015 is transformed to crop fields and the remaining 50 percent is converted to perennial plants (using oil palm as a representative). Likewise, in scenario S3, 50 percent of the abandoned rice fields available in 2015 are assumed to be transformed to crop fields and another 50 percent to oil palm. Accordingly, the total amount of GHG emissions of scenarios S2 and S3 could be calculated using Equations (13) and (14), respectively, where $LMCO_{S2}$ and $LMCO_{S3}$ are the total GHG emissions from land transformation (tonne CO_2 eq.) under scenarios S2 and S3, respectively; and A_{S2} and A_{S3} are the size of the land transformed (ha) in scenarios S2 and S3, respectively.

$$LMCO_{S2} = (0.5 \times A_{S2} \times EFLUC_{Forest\ to\ crop}) + \left(0.5 \times A_{S2} \times EFLUC_{Forest\ to\ perennial\ plant}\right) \quad (13)$$

$$LMCO_{S3} = \left(0.5 \times A_{S3} \times EFLUC_{Abandoned\ land\ to\ crop}\right) + \left(0.5 \times A_{S3} \times EFLUC_{Abandonded\ land\ to\ perennial\ plant}\right) \quad (14)$$

2.2.3. Water Consumption

Irrigation water demand was considered in this study. The total irrigation water use of the country under each simulation scenario was computed using Equations (15)–(17), where *TQwater* is the total irrigation water use of the country; $Qwater_j$ denotes the total irrigation water used by sector *j*; a_water_j is the coefficient for irrigation water use of sector *j*; XST_j stands for the production output of sector *j*; and $QwaterO_j$ and $XSTO_j$ refer to the initial values of irrigation water used by sector *j* and the production output of sector *j*, respectively.

The total irrigation demand by agricultural subsectors ($Qwater_j$) are presented in Table 3. This study followed the method to derive the total irrigation demand of Kaenchan et al. [8] in which the amount of irrigation water required by the agricultural subsectors were calculated based on the actual amount of irrigation water used in the irrigated areas.

$$TQwater_t = \sum_j Qwater_j \quad (15)$$

$$Qwater_j = a\_water_j \times XST_j \quad (16)$$

$$a\_water_j = \frac{QwaterO_j}{XSTO_j} \quad (17)$$

Table 3. Irrigation demand by agricultural subsectors.

Agricultural Subsectors		Cultivated Area (ha) [a]	Irrigation Demand (m^3/ha) [b]	Total Irrigation Demand (Million m^3) [c]
Rice farming	Wet season rice	9,290,156	481	11,944
	Dry season rice	1,353,721	5526	
Maize cultivation		1,053,935	40	42
Tapioca cultivation		1,491,155	765	1140
Sugarcane cultivation		1,534,632	765	1173
Oil palm plantation		813,296	463	377

Notes: Cultivated area is the dimension of land use in 2015 from Table 2; [c] = [a] × [b].

2.2.4. Fossil Fuel Consumption

The effect of biofuel crop expansion on fossil resource depletion was estimated from the change in production outputs of the coal and lignite mining sector and the petroleum and natural gas drilling sector that could be directly obtained from the execution of the model.

After the environmental impacts of the simulation scenarios were derived, the impacts were characterized into damage categories, i.e., damage to human health, ecosystems, and resources, by using the endpoint characterization factors in the life cycle impact assessment (LCIA) method, as illustrated in Table 4. The damage to human health is represented in units of Disability Adjusted Life Year (DALY), the damage to ecosystems is presented in units of Potentially Disappeared Fraction of species (PDF.m^2.yr), and the damage to resources is quantified in monetary units. The damages could be converted into monetary units (THB) on the basis of the monetary conversion factors provided by Kaenchan and Gheewala [33]. However, before being utilized, the monetary conversion factors were adjusted for the time value of money following Haputta et al. [34] as explained in Equation (18) where MCF_{2017} indicates the value of monetary conversion factor in 2017; MCF_y denotes the value of monetary conversion factor in the year that it was initially calculated (year y); and r is an average inflation rate of Thailand over 2008–2017, i.e., approximately 0.02 [35]. The monetary conversion factors that were adjusted for the time value of money are shown in Table 5.

$$MCF_{2017} = MCF_y \times (1 + r)^{(2017-y)} \quad (18)$$

Table 4. Endpoint characterization factors for the considered environmental impacts.

Midpoint Impact Category	Characterized Unit at Midpoint	Endpoint Characterization Factors		
		Human Health (DALY/Characterized Unit at Midpoint)	Ecosystems (PDF.m^2.yr/Characterized Unit at Midpoint)	Resources (USD_{2008}/Characterized Unit at Midpoint)
Global warming potential	CO_2 eq.	1.40×10^{-6}	5.36×10^{-1}	-
Natural land transformation (from forest to agricultural land)	m^2	-	7.90×10	-
Water depletion	m^3	1.59×10^{-7}	1.32×10^{-1}	-
Fossil depletion	kg oil eq.	-	-	1.65×10^{-1}

Notes: Endpoint characterization factors for global warming potential, natural land transformation, and fossil depletion were based on Goedkoop et al. [31]; the endpoint characterization factors of ecosystems for global warming and natural land depletion, denoted as "species.yr" in Goedkoop et al. [31], were converted to the unit of PDF.m^2.yr by computing a ratio per the total number of species in a square meter (1,604,000 global species/1.08×10^{14} m^2 surface area); and the endpoint characterization factors for water depletion were obtained from Pfister et al. [36].

Table 5. Monetary conversion factors for endpoint damages.

	THB_{2017}/DALY	THB_{2017}/PDF.m^2.yr	THB_{2017}/kg Oil Eq. (THB_{2017}/USD_{2008})
Monetary Conversion Factor	576,595	1.00	6.70 (40.63)

All modifications incorporated in this extended CGE model enabled the in-depth investigation of simultaneous interactions between economic activities and environmental factors (e.g., GHG emission, land transformation, water demand and energy consumption). In particular, this framework provided the analytical foundation for circular economy analyses, allowing researchers and policymakers to conduct a cost–benefit assessment in order to achieve a sustainable growth path.

3. Results and Discussion

3.1. Conventional GDP and Other Economic Impacts

The change in conventional GDP and other macroeconomic impacts of the simulation scenarios are shown in Table 6. The direction of macroeconomic impacts among all scenarios were almost identical. Biofuel crop expansion and biofuel production could help generate more jobs, thus increasing employment. Such increase subsequently would raise household income and private consumption in the country. Concurrently, the government could earn more income taxes, leading to increased government income. Increasing domestic production and consumption simultaneously would encourage more exports, imports, and investment. As shown in Table 6, as the percent increase in exports was much higher than that of imports in all scenarios, biofuel promotion could bring about a trade surplus. The positive change in these macroeconomic indicators contributed to higher GDP at market price. The consumer price index, which is the representative price of all products purchased by households, of scenarios S1 and S2 was slightly higher due to the reduction in rice production (the explanation on the decrease in rice production is in the last paragraph of this section). By contrast, it was slightly lower in scenario S3 when the effect of biofuel crop expansion on rice production was eliminated. By considering GDP at market price along with the consumer price index (CPI), positive changes in real GDP in all scenarios were obtained.

Table 6. Macroeconomic impacts of biofuel crop expansion (% change from BAU).

Indicators	S1	S2	S3
GDP at market price	0.098	0.098	0.103
Consumer price index	0.006	0.006	−0.004
Real GDP	0.091	0.092	0.107
Employment	0.219	0.219	0.237
Export	0.112	0.112	0.120
Import	0.061	0.061	0.065
Private consumption	0.053	0.053	0.059
Government income	0.090	0.090	0.105
Household income	0.096	0.096	0.098
Gross fixed capital formation	0.154	0.155	0.172

Following Table 6, the economic impacts of scenarios S1 and S2 were mostly similar; however, the change in real GDP of scenario S2 was slightly higher than that of scenario S1. The change in real GDP was largest in scenario S3. This result showed that utilizing abandoned rice fields for agriculture is the best option for biofuel development from an economic point of view.

By multiplying the change in the real GDP of each scenario in Table 6 with the 2017 real GDP of 10,248 billion THB, the values of the change in the real GDP of scenarios S1–S3 of approximately 9, 9, and 12 billion THB, respectively, were derived. Accordingly, the values of conventional real GDP that could be used for Green GDP calculation (following Equation (1)) of scenarios S1–S3 were 10,257, 10,257, and 10,260 billion THB, respectively.

Table 7 shows the sectoral impacts of simulation scenarios in terms of percent change from BAU. The results demonstrated that biofuel promotion could reduce the production capability of several industries such as petroleum and natural gas, textile, rubber and plastic, iron and steel, engine, and electrical machinery and parts as shown in their lower output and employment in all biofuel promoting scenarios. The reason is to serve higher productions of biofuels. Simultaneously, labor mobility occured between these sectors to palm oil production, tapioca milling, and sugar milling.

Table 7. Sectoral impacts of biofuel crop expansion (% change from BAU).

Sector Number	Activities	S1		S2		S3	
		Output	Employment	Output	Employment	Output	Employment
1	Rice cultivation	−0.02	0.01	−0.01	0.01	0.20	0.12
2	Maize cultivation	0.03	0.07	0.03	0.07	0.17	0.01
3	Tapioca cultivation	6.20	3.98	6.20	3.98	6.20	3.98
4	Sugarcane cultivation	4.50	0.52	4.50	0.52	4.50	0.52
5	Oil palm plantation	3.70	0.22	3.70	0.22	3.70	0.22
6	Livestock	0.05	0.21	0.05	0.22	0.06	0.24
7	Forestry	0.00	0.00	0.00	0.00	0.00	0.01
8	Fishery	0.03	0.12	0.03	0.12	0.03	0.13
9	Other agricultural activities	0.01	0.03	0.01	0.03	0.09	0.08
10	Coal and lignite mining	0.01	0.02	0.01	0.02	0.01	0.03
11	Petroleum and natural gas	−0.09	−0.26	−0.09	−0.26	−0.09	−0.25
12	Other mining and quarrying	0.04	0.14	0.04	0.14	0.05	0.15
13	Other food manufacturing	0.13	0.44	0.13	0.44	0.15	0.48
14	Palm oil production	3.35	12.63	3.35	12.63	3.35	12.64
15	Rice milling	−0.02	−0.04	−0.01	−0.03	0.22	0.47
16	Tapioca milling	5.67	15.17	5.67	15.17	5.67	15.17
17	Maize drying and grinding	0.05	0.12	0.05	0.12	0.06	0.15
18	Sugar refinery	4.51	15.93	4.51	15.93	4.51	15.93
19	Textile production	−0.03	−0.09	−0.03	−0.09	−0.03	−0.09
20	Wood and furniture production	0.01	0.01	0.01	0.01	0.01	0.02
21	Paper production and printing	0.01	0.02	0.01	0.02	0.01	0.02
22	Chemical production	0.08	0.23	0.08	0.23	0.08	0.24
23	Petroleum refinery	0.02	0.10	0.02	0.10	0.03	0.12
24	Rubber and plastic production	−0.06	−0.17	−0.06	−0.17	−0.05	−0.14
25	Other non-metallic production	0.04	0.13	0.04	0.13	0.05	0.14
26	Iron and steel production	−0.04	−0.10	−0.04	−0.10	−0.04	−0.11
27	Fabricate metal production	0.00	0.00	0.00	0.00	0.00	0.00
28	Engine production	−0.01	−0.02	−0.01	−0.02	−0.01	−0.02
29	Electrical machinery production	−0.03	−0.13	−0.03	−0.13	−0.04	−0.14
30	Other manufacturing	−0.04	−0.09	−0.04	−0.09	−0.04	−0.09
31	Electricity production	0.07	0.18	0.07	0.18	0.08	0.19
32	Construction	0.08	0.25	0.08	0.25	0.09	0.28
33	Trade	0.11	0.46	0.11	0.46	0.12	0.51
34	Rail transportation	0.08	0.09	0.08	0.09	0.09	0.09
35	Road transportation	0.07	0.17	0.07	0.17	0.07	0.18
36	Water transportation	0.03	0.09	0.03	0.09	0.03	0.09
37	Air transportation	0.00	0.01	0.00	0.01	0.00	0.01
38	Other transportation	0.01	0.03	0.01	0.03	0.01	0.04
39	Services	0.05	0.09	0.05	0.09	0.05	0.10

Note: The impact on employment depends on the elasticity of substitution between production factors (Table A2 of Appendix A).

The expansion of biofuel crops led to a positive change in the production of all agricultural subsectors except for rice cultivation in scenarios S1 and S2. The enhancement of household income due to biofuel promoting policies drives the demand for agricultural products higher. Thus, the production of livestock, fishery, and other agricultural products increase. Based on scenario S1, the expansion of biofuel crops had a negative impact on the production capacity of rice cultivation and milling when the agricultural land was constant. A small negative effect on the production capacity of rice cultivation and rice milling was still found in scenario S2, where approximately 3270 ha of forest was transformed to agricultural land. More land would be required for agriculture to eliminate the negative change in output and employment in scenario S2. Utilizing abandoned rice fields (scenario S3) for agriculture could enhance the economic production of all agricultural subsectors, especially rice cultivation. Nevertheless, it brought about higher adverse impacts on the production capability and employment of iron and steel production and electrical machinery and parts industries than in scenarios S1 and S2. The reason is because workers of these sectors move to palm oil production, tapioca milling, and sugar milling to serve the increased productions of biofuels.

These obtained results are in accordance with those reported in previous publications using CGE models for examining the economy-wide impacts of biofuel policies in the case of Thailand [9,10]. Specifically, this study's simulation outcomes similarly showed that the expansion of biofuels could induce substitution effects on sectoral productions, leading to the manufacturing contraction of petroleum and natural gas. On the other hand, all participants in the biofuel supply chain (e.g., tapioca, sugarcane, and oil palm plantations) could benefit from this structural shift. Likewise, the macroeconomic indicators obtained from this study's simulations align with those shown in Phomsoda et al. [9] and Phomsoda et al. [10], indicating the same range of variation in real GDP and the essential role of productivity improvement on inflation (i.e., the percentage change of CPI).

3.2. Environmental Impacts

The change in environmental impacts (compared with the BAU) from the CGE model are exhibited in Table 8. The increase in global warming was highest in scenario S3, as greater the economic activity (real GDP in Table 6 and production output in Table 7), greater the consumption of energy and chemical fertilizers. The values of change in global warming outside the blanket in Table 8 was calculated only on the basis of the amount of GHG emissions from energy consumption and chemical fertilizer use. They were not combined with GHG emissions from land transformation. After combining with GHG emissions from land transformation, the increasing rate of global warming in scenarios S2 and S3 compared with the BAU changed to 0.241 percent and 0.004 percent, respectively, as shown in the parentheses. The high increasing rate of global warming in scenario S2 was contributed by GHG emissions from forest land clearing and the loss of carbon stock in biomass and soil (aboveground and belowground carbon stocks). By contrast, the low increasing rate of global warming in S3 was due to a small amount of GHG emissions from the abandoned land clearing and a slight loss of biomass carbon stocks. In addition, transforming the abandoned rice field to the agricultural land helped increase soil organic carbon (belowground carbon stock). Therefore, the reduction in GHG from increasing soil organic carbon was greater than the GHG emissions from land clearing and biomass carbon stock loss under the land transformation in scenario S3.

Table 8. Environmental impacts due to biofuel crop expansion (% change from BAU).

Impact Categories		S1	S2	S3
Global warming		0.075 (0.075)	0.075 (0.241)	0.083 (0.004)
Land transformation (from forest to agricultural land)		0.000	0.020	0.000
Water depletion		0.924	0.927	1.101
Fossil depletion	Coal and lignite	0.006	0.007	0.007
	Petroleum and natural gas	−0.087	−0.087	−0.085

Notes: Global warming of the BAU is 254 million tonnes CO_2 eq. (the amount of CO_2 emissions from energy use in 2015 was used as it is the most updated amount) [27]; the BAU values in 2017 for other environmental impacts are as follows: forest area = 16.35 million ha [23], irrigation water use = 14,676 million m^3 (i.e., the sum of the numbers in the column [c] of Table 3), coal and lignite consumption = 13,850 ktoe [37], and petroleum and natural gas consumption = 85,370 ktoe [37].

The effect of land transformation on ecosystem health was considered in the impact category of land transformation. In this case, only the transformation of forest to agricultural land was considered to have an effect on ecosystems. Therefore, only the transformation of forest to agricultural land was considered in Table 8, and thus, a 0.02 percent increase in land transformation was presented under scenario S2. Water depletion showed the volume of irrigation water demand in each scenario. More irrigation water was required in all scenarios, especially in scenario S3, implying that more biofuel crop cultivation could lead to increased demand for water and that the volume of water required is positively correlated to the area of agricultural land. As the dimension of agricultural area in scenario S3 was larger than that in the other scenarios after accounting for land transformation, scenario S3 required more water than scenarios S1 and S2. As for fossil depletion, a reduction in petroleum and natural gas use could be observed, while the consumption of coal and lignite was higher in all scenarios. The consumption of petroleum and natural gas was reduced as a result of the substitution of conventional fuels, i.e., gasoline and diesel, by biofuels. However, the increase in the production of electricity and chemical products led to more consumption of coal and lignite. Such increase in the production of electricity and chemical products was driven by more economic activities (as shown in Tables 6 and 7).

The value of environmental impacts after adjusting for the change in Table 8 could be obtained from combining the BAU of the impacts with the product of the BAU and the percent change of environmental impacts in Table 8. The obtained values were expressed in Table A4 of Appendix A. Then, the impacts in Table A4 were transformed into endpoint damages by using the characterization factors in Table 4. The endpoint damages of each scenario are shown in Table A5 of Appendix A.

3.3. Environmental Costs

The environmental costs are presented in Table 9. The costs were obtained by multiplying the environmental impacts in Table A5 with the monetary conversion factors in Table 5. In Table 9, the total environmental cost of each scenario was computed on the basis of Equation (2). The total environmental cost of scenario S2 was the highest among all scenarios due to the effects of forest transformation that induces CO_2 emissions higher and causes a loss of biodiversity on land. This finding also showed that converting a small piece of forest land (in this case, approximately 3300 ha) could lead to more environmental impacts than the transformation of large abandoned land (in this case, 164,800 ha). The lowest total environmental cost of BAU scenario implied that biofuel crop expansion could bring about adverse environmental impacts. However, the impacts could be alleviated by utilizing abandoned rice fields as the total environmental cost of scenario S3 was lower than that of the other biofuel crop expansion scenarios (scenarios S1 and S2).

Table 9. Environmental costs incurred by biofuel crop expansion.

Impact Categories	Environmental Costs (Billion THB_{2017})			
	BAU	**S1**	**S2**	**S3**
Global warming (*COP*)	341.30	341.56	342.13	341.32
Land transformation (from forest to agricultural land) (*COL*)	0.00	0.00	2.57	0.00
Water depletion (*CWD*)	1.35	3.31	3.31	3.31
Fossil depletion (*CFD*)	0.67	0.66	0.66	0.66
Total (*TEC*)	343.31	345.53	348.67	345.30

3.4. Green GDP

The total environmental cost of each scenario in Table 9 was subtracted from its conventional GDP following Equation (1) to derive the Green GDP of each scenario. The Green GDP of each scenario is illustrated in Table 10. The highest Green GDP of all scenarios could be found in scenario S3, where biofuel crops were expanded along with the utilization of abandoned rice fields. Despite having higher environmental cost than the BAU, the Green GDP of all biofuel expansion scenarios were still higher than that of the BAU scenario. The increase in conventional GDP of all biofuel expansion scenarios could compensate for their higher environmental cost compared with the BAU scenario. Thus, considering Green GDP as an index for sustainable economic growth, biofuel crop expansion could be a policy leading towards sustainable development. However, as the Green GDP in scenario S2 was smaller than those of scenarios S1 and S3, expanding biofuel crops with forest transformation was considered to be less desirable. Policymakers should issue a law to prevent the transformation of forest to agricultural land, especially in remote areas.

Table 10. Conventional GDP, Green GDP, and GDP and environmental cost of the country.

Indicators	BAU	S1	S2	S3
Conventional GDP (real value) (billion THB)	10,248	10,257	10,257	10,260
Green GDP (real value) (billion THB)	9905	9912	9909	9914
GDP/monetary value of environmental damage	29.85	29.69	29.42	29.71

The GDP per unit of environmental cost in all scenarios showed that the value of economic production accounted for 29–30 times of the value of environmental damage. Furthermore, the GDP per unit of environmental cost was found to be the greatest in the BAU scenario, followed by scenarios S3, S1, and S2. As the GDP per unit of environmental cost implies how much value of economic production is contributed by one unit of environmental cost, an occurrence of environmental damage (derived from resource depletion and environmental degradation) in the BAU scenario was the most worthwhile. Therefore, where the efficiency of resource use and environmental degradation is considered, scenario S3, whose Green GDP is highest, may not be the best option. The policy under scenario S3 could maximize net social welfare, but it was not the most efficient scenario in terms of resource use and environmental degradation. Reduction in resource use, especially for water, and GHG emissions should be considered to achieve efficiency and welfare maximization. As biofuel crops expansion brings about larger water consumption and more GHG emissions (as a result of the enhancement of economic production), production technologies that can increase the productivity of sugarcane and oil palm cultivation and decrease GHG emissions should be applied. For example, green-cane cutting and mechanization should be utilized for sugarcane harvesting instead of burnt-cane cutting. Following Silalertruksa et al. [38] and Pongpat et al. [39], green-cane cutting and mechanization could provide more productivity for sugarcane cultivation than burnt-cane cutting while they generate less GHG emissions. Moreover, more serious regulations on industrial pollution control may help reduce GHG emissions.

Considering the pros and cons, as the efficiency of resource use and environmental degradation could be improved, the decision on biofuel crop expansion should be initially made based on economic welfare (in this case, Green GDP). Then, the policy to achieve increased efficiency can be improved. Therefore, this study showed that biofuel crop expansion could help enhance national economic welfare, and the most viable option for biofuel crop expansion is utilizing abandoned rice fields for agriculture. However, along with this policy, an improvement of production technologies and environmental mitigation measures to encourage more efficiency should be implemented.

4. Conclusions

In this study, the effects of biofuel crop expansion on Green GDP, the conventional GDP that is adjusted for environmental cost, were estimated. Three scenarios related to biofuel crop expansion policies were set to provide some policy implications towards sustainable biofuel development in Thailand. CGE modeling was used to estimate Green GDP of each scenario. Calculations based on LCIA were conducted, along with monetary conversion factors, to convert them into monetary units (environmental cost) to incorporate the environmental impacts (environmental degradation and resource depletion caused by GHG emissions, water resource use, land use, and fossil consumption) into the estimation. The results of the study could be concluded as follows:

- Biofuel crop expansion can help enhance economic growth and employment, but it can also lower the production of rice and some industrial outputs, which could be partially compensated by land expansion. As Green GDP, representing the net social welfare, for biofuel crop expansion policies was greatest when the abandoned rice fields are utilized for cultivation, this policy is recommended to be promoted.
- However, considering GDP per environmental cost, the policy of expanding biofuel crops along with utilizing abandoned rice fields for agriculture is still not the most efficient option. The efficiency of resource use and environmental degradation under this policy should be enhanced through technological improvements to achieve welfare maximization and efficiency. Furthermore, the government should support research on the productivity improvement of sugarcane and oil palm production and launch some environmental impact mitigating policies such as promoting green-cane cutting for sugarcane harvesting and supporting the utilization of alternative fuels in cultivation to encourage greater efficiency of natural resource use and environmental degradation.
- Increasing the cultivation of biofuel crops utilizing abandoned rice fields for agriculture may decrease the production capability and employment of iron and steel production and electrical machinery and parts industries. The reason is that the labor of these sectors moves to palm oil production, tapioca milling, and sugar milling to serve the increase in productions of biofuels. Increasing labor productivity by increasing the machinery to labor ratio, improving labor skill, and increasing working hours (overtime) can be considered to eliminate the labor shortage in iron and steel production and electrical machinery and parts industry.
- Expanding biofuel crop cultivation areas and utilizing forest areas provides even lower Green GDP than the scenario in which there is no land transformation, and its GDP per environmental cost is the lowest among all scenarios. This policy is thus considered inefficient. Therefore, strict laws and regulations must exist to prevent the illegal transformation of forest to agricultural land, especially in remote areas. Additionally, the governmental agency in charge should carefully make considerations on providing concessions for the regulated use of forest areas for other purposes, especially for oil palm plantation that has previously been mentioned.

The results of this study can support policymakers in making decisions on biofuel crop expansion. The provided information on environmental impacts can serve as a guideline for resource management and planning as well as environmental impact mitigating policies. The method to derive the effect of policy to Green GDP presented in this study is novel and can also be used for assessing the annual Green GDP of a country. Moreover, it can be applied to estimate the sustainability of public policies for which Green GDP is taken as an indicator.

For future policy formulations, the use of a dynamic CGE model would be preferable, especially for examining the dynamic adjustment and the long-term impact. Additionally, in this study, the rental rates of a few land use types were assumed. The actual rental rate of those land use types, if available, can instead be applied in future research.

Author Contributions: Conceptualization, P.H. and S.H.G.; data curation, P.H. and T.B.; formal analysis, P.H. and T.B.; funding acquisition, P.H.; investigation, P.H. and T.B.; methodology, P.H., T.B., N.P. and S.H.G.; project administration, P.H. and S.H.G.; resource, P.H. and S.H.G.; software, T.B. and N.P.; supervision, P.H. and S.H.G.; validation, T.B., N.P. and S.H.G.; visualization, P.H. and T.B.; writing—original draft preparation, P.H.; writing—review and editing, N.P. and S.H.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science and Technology Development Agency (NSTDA) and King Mongkut's University of Technology Thonburi (KMUTT). The article processing charge was supported by Thammasat University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This study was jointly carried out under the project "Network for Research and Innovation for Trade and Production of Sustainable Food and Bioenergy" supported by NSTDA and the post-doctoral fellowship program of KMUTT.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

AEDP	Alternative Energy Development Plan
BOT	Bank of Thailand
BAU	Business-as-usual
CGE	Computable general equilibrium
CPI	Consumer price index
DALY	Disability Adjusted Life Year
DEDE	Department of Alternative Energy Development and Efficiency
EPPO	Energy Policy and Planning Office
GIS	Geographic Information System
GPI	Genuine Progress Indicator
GHG	Greenhouse gas
GDP	Gross Domestic Product
ISWE	Index of Sustainable Economic Welfare
OAE	Office of Agricultural Economics
LDD	Land Development Department
LCIA	Life cycle impact assessment
NESDC	National Economic and Social Development Council
NSO	National Statistical Office
PEP	Partnership for Economic Policy
PDF	Potentially Disappeared Fraction of species
SAM	Social Accounting Matrix
THB	Thai baht
TGO	Thailand Greenhouse Gas Management Organization

Appendix A

Table A1. List of sectors and commodities in CGE model.

I-O Code [a]	Sector Number	Activities	Product Number	Products
001	1	Rice cultivation	1	Rice
002	2	Maize cultivation	2	Maize
004	3	Tapioca cultivation	3	Tapioca
009	4	Sugarcane cultivation	4	Sugarcane
011	5	Oil palm plantation	5	Oil palm
018-023	6	Livestock	6	Livestock
025-027	7	Forestry	7	Forest products
028-029	8	Fishery	8	Fish
003, 005-008, 010, 012-017, 024	9	Other agricultural activities	9	Other agricultural products
030	10	Coal and lignite mining	10	Coal and lignite
031	11	Petroleum and natural gas	11	Petroleum and natural gas
032-041	12	Other mining and quarrying	12	Mineral
042-046, 047-048, 052-054, 056-066	13	Other food manufacturing	13	Other food
047B	14	Palm oil production	14	Palm oil
049	15	Rice milling	15	Milled rice
050	16	Tapioca milling	16	Tapioca products
051	17	Maize drying and grinding	17	Grinded maize
055	18	Sugar refinery	18	Sugar
067-074	19	Textile production	19	Fabric
078-080	20	Wood and furniture production	20	Wooden products
081-083	21	Paper production and printing	21	Paper and printing products
084-092	22	Chemical production	22	Chemicals
093, 094, 136	23	Petroleum refinery	23	Petroleum products
095-098	24	Rubber and plastic production	24	Rubber and plastic
099-104	25	Other non-metallic production	25	Other non-metallic products
105-107	26	Iron and steel production	26	Iron and steel
108-111	27	Fabricate metal production	27	Fabricate metal
112-115, 123-128	28	Engine production	28	Engines
116-122	29	Electrical machinery production	29	Electrical machinery
075-077, 129-134	30	Other manufacturing	30	Products from other manufacturing
135	31	Electricity production	31	Electricity
138-144	32	Construction	32	Infrastructures
145-146	33	Trade	33	Trade
149	34	Rail transportation	34	Rail transportation
150-152	35	Road transportation	35	Road transportation
153-155	36	Water transportation	36	Water transportation
156	37	Air transportation	37	Air transportation
157	38	Other transportation	38	Other transportation
137, 147-148, 158-180	39	Services	39	Services

Note: [a] is based on NESDC [19].

Table A2. Parameters of elasticity of substitution.

Sector Number [Industry (*j*)]	Elasticity of Substitution between Capital–Land Composite and Labor [a]	Elasticity of Substitution between Capital and Land [b]	Sector Number [Industry (*j*)]	Elasticity of Substitution between Capital–Land Composite and Labor	Elasticity of Substitution between Capital and Land
1	0.20	0.20	21	1.50	0.50
2	0.20	0.20	22	1.50	0.50
3	0.20	0.43	23	1.50	0.50
4	0.20	0.20	24	1.50	0.50
5	0.20	0.20	25	1.50	0.50
6	0.20	0.20	26	1.50	0.50
7	0.20	0.20	27	1.50	0.50
8	0.20	0.20	28	1.50	0.50
9	0.20	0.20	29	1.50	0.50
10	1.50	0.50	30	1.50	0.50
11	1.50	0.50	31	1.50	0.50
12	1.50	0.50	32	1.50	0.50
13	1.50	0.50	33	1.50	0.50
14	1.50	0.50	34	1.50	0.50
15	1.50	0.50	35	1.50	0.50
16	1.50	0.50	36	1.50	0.50
17	1.50	0.50	37	1.50	0.50
18	1.50	0.50	38	1.50	0.50
19	1.50	0.50	39	1.50	0.50
20	1.50	0.50	-	-	-

Notes: Values in [a] were calculated following OECD/ILO [20]; values in [b] were determined based on the assumption that the elasticity of substitution between capital and land of agricultural subsectors are lower than that of other sectors because the agricultural subsectors are land intensive and the substitution of capital for land is rigid; the elasticity of substitution between capital and land of sector 3 (tapioca cultivation) is assumed to be higher than that of other agricultural subsectors, allowing more flexibility for the substitution of capital for land. Thus, this sector requires a lower marginal land for producing marginal output; for other types of elasticity, the standard elasticity parameters in Decaluwé et al. [17] were employed; the elasticity of transformation of sector *j* was set to 2.0; the elasticity of transformation between exports and domestic sales of product *i* of sector *j* was set to 2.0; the elasticity of substitution between imported and domestically produced commodity of product *i* was set to 2.0.

Table A3. Values of the parameters in Equations (8)−(10).

Parameters		Units	Values
Aboveground biomass of forest		tonne carbon C/ha	162.45
Aboveground biomass of set-aside land		tonne C/ha	7.58
Soil organic carbon (SOC) of forest land		tonne C/ha	47
SOC of cropland		tonne C/ha	45.34
SOC of oil palm		tonne C/ha	63.65
SOC of set-aside land		tonne C/ha	43.26
GHG emissions from forest land clearing	CO_2 emissions	tonne CO_2 eq./ha	261.42
	Non-CO_2 GHG emissions	tonne CO_2 eq./ha	37.99
GHG emissions from set-aside land clearing	CO_2 emissions	tonne CO_2 eq./ha	-
	Non-CO_2 GHG emissions	tonne CO_2 eq./ha	0.91
Time span of field crop		year (yr)	4
Time span of oil palm		yr	25

Notes: All values were derived based on the method of calculation introduced in Silalertruksa and Gheewala [32] and information from JGSEE [40] and IPCC [41].

Table A4. The environmental impacts after adjusting for the change in Table 8.

Impact Categories	BAU	S1	S2	S3
Global warming potential (million tonne CO_2 eq.)	254.43	254.62	255.04	254.44
Land transformation (from forest to agricultural land) (ha)	0.00	0.00	3,269.00	0.00
Water depletion (million m^3)	14,676.23	14,811.84	14,812.28	14,837.82
Fossil depletion (KTOE)	99,220.00	99,146.72	99,146.75	99,148.12

Table A5. Endpoint damages to the safeguard subjects, human health, ecosystem, and resources in each scenario.

Scenarios	Midpoint Impact Categories	Damage Categories		
		Human Health (DALY)	Ecosystems (PDF.m^2.yr)	Resources (USD$_{2008}$)
BAU	Global warming	3.6×10^5	1.4×10^{11}	0.0×10^0
	Land transformation	0.0×10^0	0.0×10^0	0.0×10^0
	Water depletion	2.3×10^3	0.0×10^0	0.0×10^0
	Fossil depletion	0.0×10^0	0.0×10^0	1.6×10^7
S1	Global warming	3.6×10^5	1.4×10^{11}	0.0×10^0
	Land transformation	0.0×10^0	0.0×10^0	0.0×10^0
	Water depletion	2.4×10^3	2.0×10^9	0.0×10^0
	Fossil depletion	0.0×10^0	0.0×10^0	1.6×10^7
S2	Global warming	3.6×10^5	1.4×10^{11}	0.0×10^0
	Land transformation	0.0×10^0	2.6×10^9	0.0×10^0
	Water depletion	2.4×10^3	2.0×10^9	0.0×10^0
	Fossil depletion	0.0×10^0	0.0×10^0	1.6×10^7
S3	Global warming	3.6×10^5	1.4×10^{11}	0.0×10^0
	Land transformation	0.0×10^0	0.0×10^0	0.0×10^0
	Water depletion	2.4×10^3	2.0×10^9	0.0×10^0
	Fossil depletion	0.0×10^0	0.0×10^0	1.6×10^7

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