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Research Article

Forest Management

Assessing Carbon Abatement Costs Considering Forest Carbon Sequestration and Carbon Offset Mechanism: Evidence from Taiwan

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Abstract

Based on the Greenhouse Gas Reduction and Management Act passed in 2015 and the carbon neutral target in 2050, Taiwan will most likely follow international trends by imposing carbon taxes and establishing carbon offset markets. The positive and negative effects of carbon taxes and carbon offset markets on the economy and the environment merit further investigation. Accordingly, this study adopted a carbon emission reduction (CER) cost prediction model to assess the carbon abatement costs under three scenarios: (1) a carbon offset market exists, and forest carbon sequestration can be used as carbon offsets; (2) a carbon offset market exists, but forest carbon sequestration cannot be used as carbon offsets; and (3) a carbon offset market does not exist. Forests in Taipei (with low carbon emissions) and Kaohsiung (with high carbon emissions) were selected as research sites to explore the benefits of carbon emissions trading and forest carbon sequestration. The results show that CER costs are the lowest in scenario 1 and are the highest in scenario 3. The CER costs of Kaohsiung are higher than those of Taipei. The higher the carbon price, the greater the difference in CER costs between the two cities.

Study Implications: The objective of this study was to identify the optimal policy for Taiwan to effectively slow climate change. This study showed that the opening of carbon offset markets and the use of forest carbon sequestration as carbon offsets may prompt regions to increase their forest stock to lower their emission reduction costs. However, achieving 2050 carbon neutral target by solely using forest carbon sequestration is not sufficient in Taiwan.

Keywords: climate change, forest carbon sequestration, carbon emission reduction (CER) cost, carbon offset market

Climate change has become a major environmental factor of ecosystem changes (Li 2008; Subramanian et al. 2015). Häder and Barnes (2019) asserted that climate change is disrupting and changing the relationship between land and water through biogeochemical and hydrologic cycles. In 2018, the Intergovernmental Panel on Climate Change (IPCC) of the United Nations indicated that human activities will cause global warming of 1.5°C from 2030 to 2052 and reiterated the serious effects of global warming on nature and human systems (IPCC 2022). Changes in rainfall patterns have contributed to changes in water quality and salinity in freshwater and estuarine ecosystems, affecting the productivity and composition of phytoplankton and aquatic plant communities in the ecosystems (White and Visser 2016). In recent years, Taiwan's average temperature and sea level have risen at rates exceeding those globally, and its seasonal rainfall has intensified. Additionally, its number of days without rainfall has increased, and the intensities of extreme rainfall in its western regions have amplified annually (Wu et al. 2010). These studies have verified the profound effects of climate change on the environment. One of the primary reasons for global warming is the increase in greenhouse gas (GHG) concentrations (IPCC 2013; Suwal et al. 2015; Zarch et al. 2017), which have increased from an average of 280 ppm before the Industrial Revolution era to 400 ppm today; this figure is expected to increase to 1,000 ppm by the end of this century (Kiehl 2011).

At present, a carbon tax or carbon payment is widely recognized as the most cost-effective carbon reduction policy (Nordhaus 2007). Its implementation facilitates the promotion of green energy, reduces the burden on the environment, diminishes the negative effects of climate change, and helps the economy and local development of underdeveloped countries (Ding et al. 2019; Lin and Ge 2019; Liu and Crillo 2016; Metcalf 2009). Li et al. (2019) concluded that carbon tax and personal carbon trading has

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a significant positive effect on the public choosing electric battery vehicles as their means of transportation. Mardones and Cabello (2019) demonstrated that by introducing an environmental tax, Chile can lower its carbon dioxide (CO_2) emissions by 11%.

To slow climate change, Taiwan passed the Greenhouse Gas Reduction and Management Act (Environmental Protection Administration of Taiwan 2015), aiming to reduce GHG emission to 50% of that in 2005 by 2050. However, the Greenhouse Gas Emissions Inventory reports released by the Environmental Protection Administration of Taiwan in recent years revealed increasing CO_2 emissions. For example, the 2018 National Greenhouse Gas Emissions Inventory Report (Environmental Protection Administration of Taiwan 2018) indicated that at 293,125 thousand metric tons of CO_2 equivalent, Taiwan's CO_2 emissions in 2016 was the highest since 2010. This number represented an increase of 1.22% from 2015 (289,581 thousand metric tons) and was equal to an average of approximately 11.24 metric tons of CO_2 emissions per person. Many studies have shown that effective control of CO_2 emissions and increasing forest carbon sequestration are useful approaches to slowing climate change (Bai et al. 2015; Carle et al. 2022; Chen et al. 2019). As climate change becomes increasingly severe, the balance between environment and economic development also becomes increasingly serious. To achieve a balance between the environment and economic development, relevant climate policies should be implemented to minimize the impact of economic development (Lin and Ge 2019).

Since September 2022, Taiwan has been revising the Greenhouse Gas Reduction and Management Act, which was announced in 2015 (Environmental Protection Administration of Taiwan 2015). Aside from setting a net-zero emission reduction target for 2050, it will also include regulations for carbon trading markets. However, there is no carbon trading market in Taiwan currently, and there is no forest carbon offset. Once a carbon trading market is established in the future, will the carbon emission reduction (CER) costs be effectively reduced? Do cities with high carbon emissions have higher CER costs? Accordingly, this study mainly explores the CER costs of different cities with different carbon emissions (including Taipei with low emissions and Kaohsiung with high emissions) under the existence of a carbon trading market and analyzes the impact of different carbon prices on CER costs. The results can also be a reference to cities in other countries or areas.

This study investigated the balance between economic development and CER under three scenarios using a CER cost prediction model. The three scenarios are as follows: (1) a carbon offset market exists, and forest carbon sequestration can be used as carbon offsets; (2) a carbon offset market exists, but forest carbon sequestration cannot be used as carbon offsets; and (3) a carbon offset market does not exist. Unlike other studies, this study used regional total income as its factor of influence to explore the CER costs expended by Taiwan to meet its CER goals and the benefits of carbon emissions trading forest carbon sequestration.

Materials and Methods

Study Site

The objective was to identify the optimal plan for Taiwan to effectively slow climate change. Because Taipei City (hereafter "Taipei") and Kaohsiung City ("Kaohsiung") contained complete relevant data and are the hubs of Taiwan's economic development, they were the cities investigated in the study (figure 1).

Timber Volume Prediction Model

This study builds a linear model to predict future forest area and forest stock volume, which are influenced by the independent variable, gross domestic product (GDP). A forest stock volume prediction model was used to predict the future forest area and forest stock volume. The formulas are given below:

$$I = U \cdot A \tag{1}$$

$$A = (1 + g_a) \cdot A_{-1} \tag{2}$$

$$A = \alpha_0 + \alpha_1 \cdot Y \tag{3}$$

where total forest stock volume I (in m^3) was obtained by multiplying forest area A (measured in ha) by unit stock volume U (measured in m^3/ha); forest area A was estimated by the forest area A_{-1} in the previous year and annual change g_a in forest area; and a linear regression was performed to determine the relationship between forest area A and total income Y (measured in \$), given coefficients α_0 and α_1.

Forest Carbon Sequestration Prediction Model

This study referenced the estimation models announced in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006), such as carbon sequestration of forests. The forest carbon sequestration volume C (measured in metric tons) is given by

$$C = (I_t - I_{t-1}) \cdot BD \cdot BEF \cdot (1 + R) \cdot CF \cdot 3.67, \tag{4}$$

where I_t is total forest stock volume (measured in m^3) of year t; BD is the basic wood density (metric ton/m^3); BEF is the biomass expansion factor; R is the ratio of below-ground biomass to above-ground biomass; and CF is the carbon fraction. The molecular mass of CO_2 and carbon are 44 and 12, respectively, creating a conversion coefficient of approximately 3.67 (i.e., 44/12 =3.67).

Carbon Trading Model

Rehdanz et al. (2006) proposed a model for calculating CER for a market consisting of multiple countries, in which the carbon offset market is established on the principle that forest carbon sequestration can be treated as a carbon emission value. This model evaluates the effects of carbon sequestration, CER, CER costs, and carbon distribution on countries.

This study modified this CER model to predict changes in CER costs for a market consisting of multiple regions with carbon sequestration and carbon offset. Our model considers two cases: the expected target volume of carbon emissions of a region is (1) greater than its carbon offset and (2) smaller than its carbon offset. We assumed that the carbon offset market consists of I regions in the first case and J regions in the second case. Then, in the first case, the CER cost C_i of each

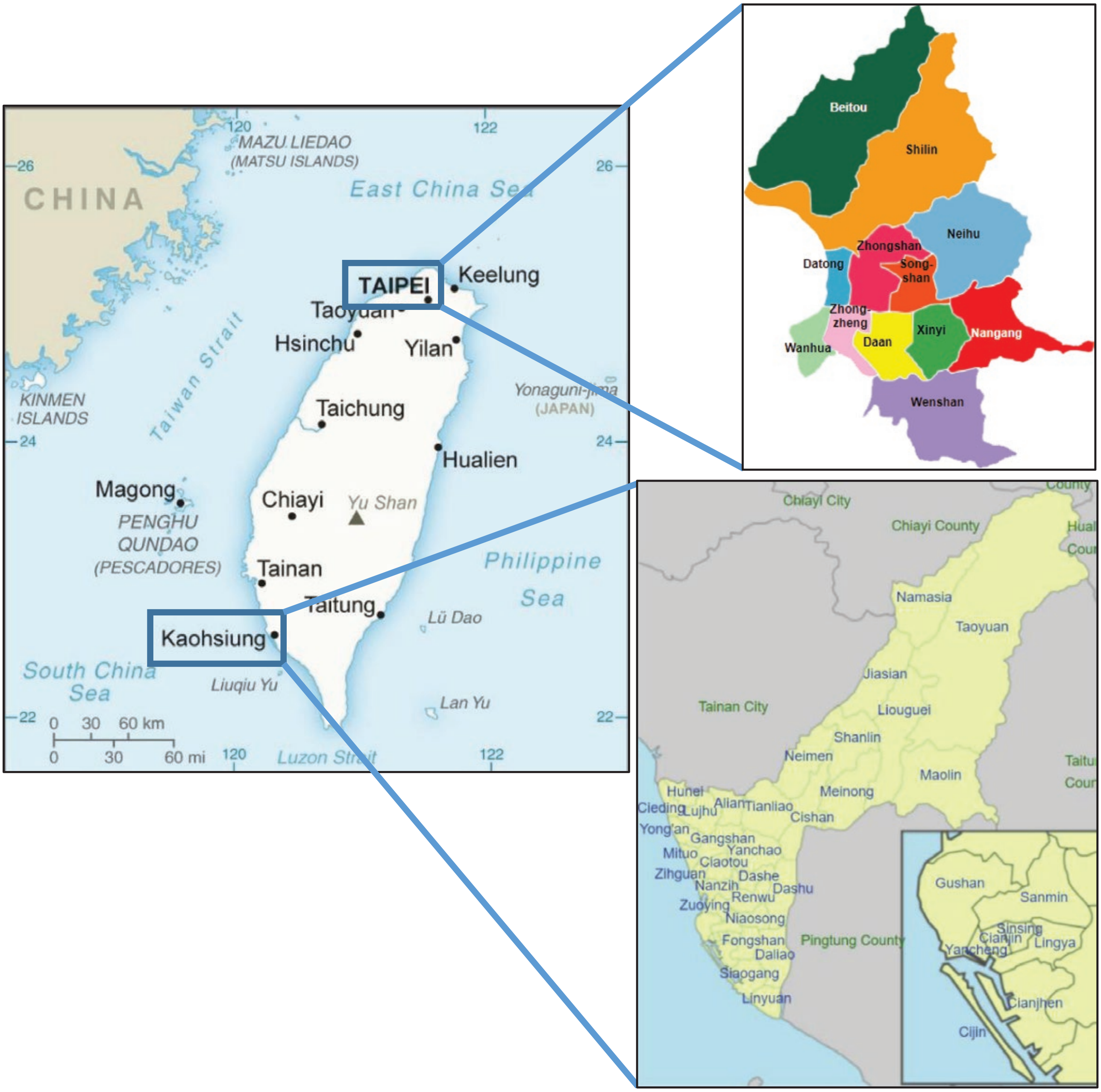

Figure 1. Geographic information of research sites: Taipei and Kaohsiung in Taiwan.

of the I regions (say, region i) can be minimized as follows (Rehdanz et al. 2006):

$$\min_{R_i,Q_i} C_i = \alpha_i \cdot R_i^2 \cdot Y_i + \pi \cdot Q_i \quad \text{s.t. } R_i \cdot E_i + Q_i \geq E_i - P_i \tag{5}$$

where α_i is a parameter that represent the coefficient of the product of income and the square of the CER rate; R_i is the CER rate of region i; Y_i is the total income (measured in \$) of region i; π is the price of carbon storage (measured in \$/metric ton); Q_i is the carbon trading volume (in metric tons) of region i; E_i is the expected target volume of carbon emissions of region i (in 10,000 metric tons); and P_i is the carbon offset (in metric tons) of region i. Therefore, from equation (5), when the expected target volume of carbon emissions (E_i) of a region is greater than its carbon offset (P_i), this region must reduce its carbon emissions (i.e., increasing the CER rate R_i) or purchase more carbon credits (i.e., $Q_i > 0$) to compensate for its excess carbon emissions.

In the second case, for each of the J regions (say, region j), the expected target volume of carbon emissions (E_j) of a region is smaller than its carbon offset (P_j). Then, region j can sell excess carbon offsets (i.e., Q_j, which is at most $|E_j - P_j|$) to other regions; and region j's surplus CER volume ($R_j \cdot E_j$) can be used as carbon credits ($\pi \cdot R_j \cdot E_j$) and sold to other regions, given by

$$\min_{R_i,Q_i} C_i = \alpha_j \cdot R_j^2 \cdot Y_j - \pi \cdot R_j \cdot E_j + \pi \cdot Q_j \text{ s.t. } \quad Q_j \geq E_j - P_j. \tag{6}$$

Table 1. Total income and economic growth rates of Taipei and Kaohsiung for the years 2020–2050.

Year	Taipei		Kaohsiung	
	Total income (in \$)	Economic growth rate (%)	Total income (in \$)	Economic growth rate (%)
2020	57,482.68	0.32%	45,623.96	1.29%
2021	57,625.65	0.25%	46,085.60	1.01%
2022	57,785.04	0.28%	46,604.16	1.13%
2023	57,970.08	0.32%	47,211.28	1.30%
2024	58,178.71	0.36%	47,902.49	1.46%
2025	58,404.97	0.39%	48,660.35	1.58%
2026	58,643.05	0.41%	49,467.28	1.66%
2027	58,888.74	0.42%	50,310.37	1.70%
2028	59,139.36	0.43%	51,181.40	1.73%
2029	59,393.93	0.43%	52,077.65	1.75%
2030	59,652.39	0.44%	52,999.55	1.77%
2031	59,914.93	0.44%	53,948.48	1.79%
2032	60,182.03	0.45%	54,926.85	1.81%
2033	60,454.19	0.45%	55,937.33	1.84%
2034	60,731.23	0.46%	56,980.17	1.86%
2035	61,012.60	0.46%	58,054.11	1.88%
2036	61,297.89	0.47%	59,158.40	1.90%
2037	61,586.75	0.47%	60,292.49	1.92%
2038	61,878.80	0.47%	61,455.61	1.93%
2039	62,173.17	0.48%	62,644.94	1.94%
2040	62,468.60	0.48%	63,855.87	1.93%
2041	62,764.48	0.47%	65,086.27	1.93%
2042	63,060.96	0.47%	66,336.98	1.92%
2043	63,358.59	0.47%	67,610.67	1.92%
2044	63,658.08	0.47%	68,910.78	1.92%
2045	63,959.87	0.47%	70,239.80	1.93%
2046	64,263.75	0.48%	71,597.39	1.93%
2047	64,568.95	0.47%	72,980.66	1.93%
2048	64,874.51	0.47%	74,385.61	1.93%
2049	65,179.32	0.47%	75,807.42	1.91%
2050	65,482.69	0.47%	77,242.78	1.89%

Note that $Q_i > 0$ in the first case means that region i purchases carbon credits whereas $Q_j < 0$ in the second case means that region j sells carbon credits.

Note that different cities have different income (Y_i) and expected carbon emissions target volume (E_i); and α_i can be obtained by substituting the income (Y_i) and expected carbon emissions target volume (E_i) into the following equation (Rehdanz et al. 2006):

$$\alpha_i = 1.57 - 0.17\sqrt{\frac{E_i}{Y_i} - \min_i \frac{E_i}{Y_i}}. \tag{7}$$

Parameter α_j for region j can be obtained similarly.

Assuming that total market supply equals total market demand, the following equation must be satisfied:

$$\sum_{i=1}^{I} Q_i + \sum_{j=1}^{J} Q_j - \sum_{j=1}^{J} R_j \cdot E_j = 0. \tag{8}$$

That is, I regions are demanders and J regions are suppliers in this market. Based on Equation (8), the aggregate market demand of carbon trading of I regions is equal to the aggregate market supply of carbon trading of J regions.

Results

Parameter Settings and Analysis

Total Income of Households

Figure 1 shows the geographic information of the research sites Taipei and Kaohsiung in Taiwan. Data for number of households and average income per household of Taipei and Kaohsiung for years 1993–2015 were released by the National Statistics of Taiwan (2019a).[1] Number of households was multiplied by average income per household for 1993–2015 to obtain the total income for each year.

[1]Total income provided by the National Statistics of Taiwan (2019a) included employment income, income from business operations, income from property, presumed income from self-use residence, regular transfer income, and miscellaneous income.

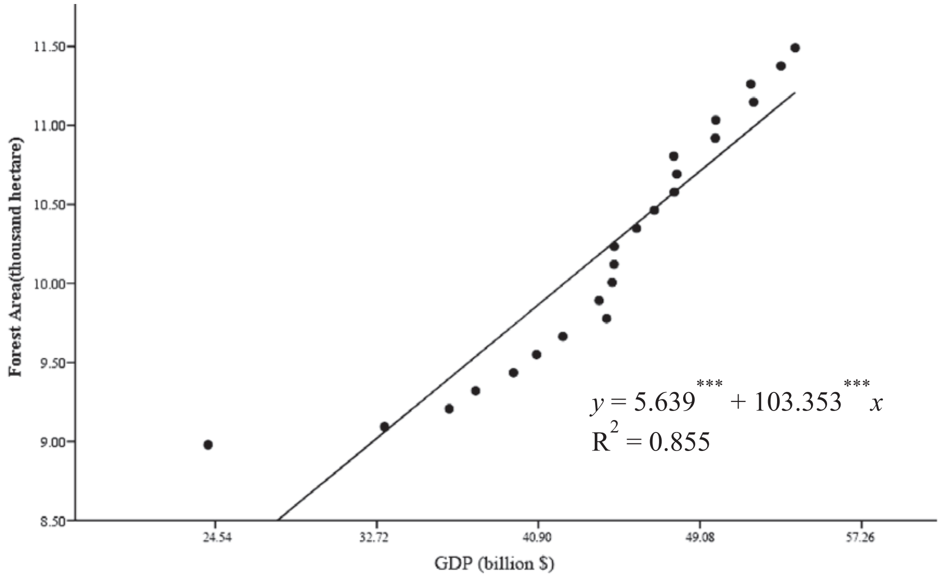

Figure 2. Correlation between total income and forest area of Taipei for 1993–2015. *P < 0.05; ** P < 0.01; *** P < 0.001.

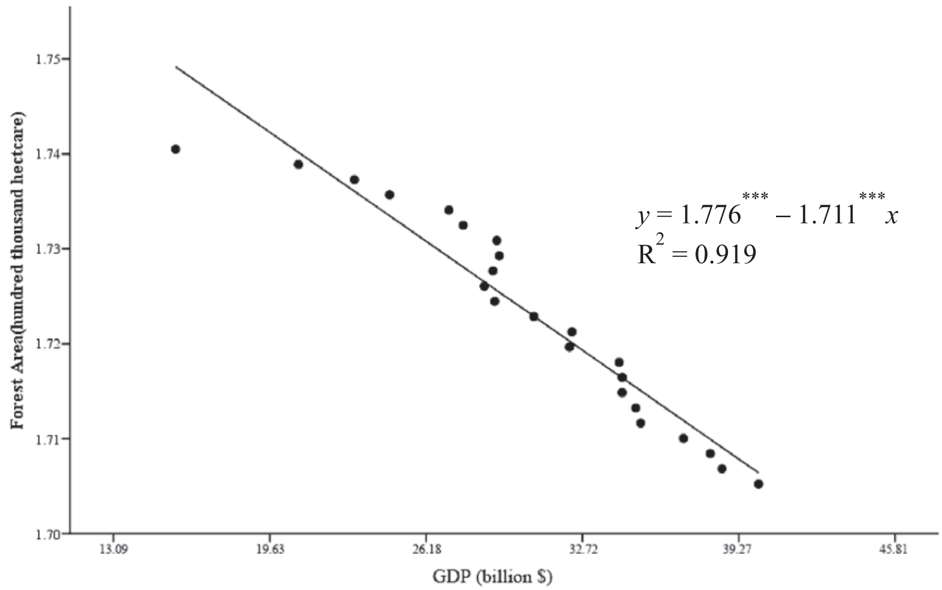

Figure 3. Correlation between total income and forest area of Kaohsiung for 1993–2015. GDP, gross domestic product. *P < 0.05; ** P < 0.01; *** P < 0.001.

It is difficult to forecast the future total income trends. For years 1993–2015, if two countries have similar competitiveness rankings, they would lead to similar trajectories in GDP. According to the 2019 World Competitiveness Yearbook published by International Institute for Management Development (IMD) and the Global Competitiveness Report from the World Economic Forum (WEF), Finland has a similar competitiveness ranking to Taiwan, and hence this study used Finland as a reference for forecasting. Referring to the forecasted annual GDPs and growth rates of Finland from 2019 to 2050 published by the Organization for Economic Cooperation and Development (OECD) (2019), this study estimated the future total income and growth rates of Taipei and Kaohsiung, as shown in Table 1.

Estimated Forest Area, Forest Stock Volume, and Unit Stock Volume

The forest areas of counties and cities[2] for the years 1993–2015 were obtained using the statistical indicators compiled by National Statistics of Taiwan (2019b). The forest stock volume of counties and cities were obtained using the 2015 forest stock volume of cities and counties (indicated in the Fourth Forest Resources Survey released by the Forestry Bureau of Taiwan 2015), and the arithmetic progression

[2]Before 2010, Taipei City and Kaohsiung City were yet to be upgraded as special municipalities. When we calculated their forest areas before 2010, those of Taipei City only referred to the forest area of Taipei City, and those of Kaohsiung City were calculated by adding those of Kaohsiung City and Kaohsiung County.

Table 2. Forecasted forest areas of Taipei and Kaohsiung for 2020–2050.

Year	Forest area (ha)	
	Taipei	Kaohsiung
2020	11,579.81	169,715.99
2021	11,594.58	169,636.65
2022	11,611.06	169,547.53
2023	11,630.18	169,443.18
2024	11,651.74	169,324.39
2025	11,675.13	169,194.13
2026	11,699.73	169,055.45
2027	11,725.12	168,910.54
2028	11,751.02	168,760.84
2029	11,777.33	168,606.80
2030	11,804.04	168,448.36
2031	11,831.18	168,285.27
2032	11,858.78	168,117.11
2033	11,886.91	167,943.44
2034	11,915.54	167,764.21
2035	11,944.62	167,579.63
2036	11,974.10	167,389.84
2037	12,003.96	167,194.92
2038	12,034.14	166,995.02
2039	12,064.56	166,790.61
2040	12,095.09	166,582.49
2041	12,125.67	166,371.02
2042	12,156.31	166,156.06
2043	12,187.07	165,937.15
2044	12,218.02	165,713.70
2045	12,249.21	165,485.28
2046	12,280.62	165,251.96
2047	12,312.16	165,014.22
2048	12,343.74	164,772.75
2049	12,375.24	164,528.38
2050	12,406.59	164,281.69

method was used to deduce forest area and forest stock volume for 2005–2015.

A linear regression analysis was performed on the total income and forest area of Taipei and Kaohsiung for 1993–2015 by using SPSS 20 to determine the correlations between forest area and total income. So far, only four large-scale surveys on forest resources in Taiwan have been conducted, in 1954–1956, 1972–1977, 1990–1993, and 2008–2014 (Forestry Bureau of Taiwan 2015). The latest forest resource survey in Taiwan (including forest area and forest stock volume) is the fourth forest resource survey in 2015. How to forecast the future forest area for years 2020–2050? Based on the literature, the economic development of a country is associated with its urban green area (Park and Kim 2019; Ramlee et al. 2015; Zhang et al. 2012). The degree of economic development of a country is often measured by GDP for analysis, and hence this study adopts GDP to represent the total income to analyze its correlations with urban forest area. Because the only information on the forest area in Taiwan is the result of the fourth forest resources survey in 2015, the future forest area for years 2020–2050 can only be estimated. Based on this, this study firstly simulated the relationship between forest area and income in 1993–2015 and, as shown in figures 2 and 3, it has more than 90% explanatory power (showing that the higher the urban income in Taiwan, the higher the forest area). Then, this study used regression to estimate the future forest area and the future income growth rate from 2020 to 2050, used forest area to estimate the forest stock volume, and calculated the future forest carbon sequestration. Table 2 shows the forecasted forest areas of Taipei and Kaohsiung for 2020–2050.

Table 3. Basic wood density, biomass expansion factor, ratio of below-ground biomass to above-ground biomass, and carbon fraction of Taiwanese forests.

	Coniferous trees	Forests with a mix of coniferous and broadleaf trees	Broadleaf trees
Basic wood density	0.41	0.49	0.56
Biomass expansion factor	1.27	1.34	1.40
Ratio of below-ground to above-ground biomass	0.22	0.23	0.24
Carbon fraction	0.48	0.48	0.47

Source: Environmental Protection Administration of Taiwan (2018).

Table 4. Annual CO_2 equivalent of Taipei and Kaohsiung for 2005–2017.

Year	Taipei	Kaohsiung
	CO_2 equivalent (in 10,000 metric tons)	CO_2 equivalent (in 10,000 metric tons)
2005	1,307.36	6,573.25
2006	1,319.32	6,563.33
2007	1,308.88	6,659.17
2008	1,321.02	5,971.51
2009	1,240.73	5,563.10
2010	1,245.80	5,935.87
2011	1,245.92	5,944.75
2012	1,219.63	5,752.58
2013	1,195.52	5,696.64
2014	1,199.16	5,686.00
2015	1,208.53	5,606.76
2016	1,240.97	5,781.49
2017	1,261.64	5,739.90

Sources: National Development Council of Taiwan (2022) and Environmental Protection Bureau, Kaohsiung City Government (2022).

Carbon Sequestration Estimation Parameters

Using data from the Greenhouse Gas Emissions Inventory reports (2018), basic wood density, biomass expansion factor, ratio of below-ground biomass to above-ground biomass, and carbon fraction of Taiwanese forests obtained using forest carbon sequestration estimation models are shown in Table 3.

Table 5. Expected carbon emissions targets and CER rates.

Year	Taipei		Kaohsiung	
	Expected carbon emissions target volume (in 10,000 metric tons of CO_2 equivalent)	CER rate (%)	Expected carbon emissions target volume (in 10,000 metric tons of CO_2 equivalent)	CER rate (%)
2020	1,196.77	1.77	5,258.60	2.96
2021	1,175.14	1.81	5,192.87	1.25
2022	1,153.52	1.84	5,127.14	1.27
2023	1,131.89	1.87	5,061.40	1.28
2024	1,110.27	1.91	4,995.67	1.30
2025	1,088.64	1.95	4,929.94	1.32
2026	1,067.02	1.99	4,864.21	1.33
2027	1,045.39	2.03	4,798.47	1.35
2028	1,023.77	2.07	4,732.74	1.37
2029	1,002.14	2.11	4,667.01	1.39
2030	980.52	2.16	4,601.28	1.41
2031	964.18	1.67	4,535.54	1.43
2032	947.84	1.69	4,469.81	1.45
2033	931.49	1.72	4,404.08	1.47
2034	915.15	1.75	4,338.35	1.49
2035	898.81	1.79	4,272.61	1.52
2036	882.47	1.82	4,206.88	1.54
2037	866.13	1.85	4,141.15	1.56
2038	849.78	1.89	4,075.42	1.59
2039	833.44	1.92	4,009.68	1.61
2040	817.10	1.96	3,943.95	1.64
2041	800.76	2.00	3,878.22	1.67
2042	784.42	2.04	3,812.49	1.69
2043	768.07	2.08	3,746.75	1.72
2044	751.73	2.13	3,681.02	1.75
2045	735.39	2.17	3,615.29	1.79
2046	719.05	2.22	3,549.56	1.82
2047	702.71	2.27	3,483.82	1.85
2048	686.36	2.33	3,418.09	1.89
2049	670.02	2.38	3,352.36	1.92
2050	653.68	2.44	3,286.63	1.96

Table 6. Carbon prices for Taiwan, Mainland China, Japan, and EU.

Country	Carbon price (\$/tCO_2 e)
Taiwan	49.08
Mainland China	12.16
Japan	2.65
EU	32.47

Sources: Word Bank (2022), Environmental Protection Administration of Taiwan (2015).

Expected Carbon Emissions Target Volume and CER Rates

Table 4 shows the annual CO_2 equivalent of Taipei and Kaohsiung for the years 2005–2017, according to the data compiled by the National Development Council of Taiwan (2022) and those of the Environmental Protection Bureau, Kaohsiung City Government (2022).

The Taipei City Self-Government Ordinance for Sustainable Living City promulgated by the Department of Environmental Protection, Taipei City Government (2022) state that their goal is to reduce the CO_2 equivalent to 75% of that in 2005 by 2030 and to 50% of that of 2005 by 2050. Given that the CO_2 equivalent of Taipei in 2005 was 13.0736 million metric tons, this signified a CO_2 equivalent of 9.8052 and 6.5368 million metric tons by 2030 and 2050, respectively.

The Plans and Actions to Transform Kaohsiung into a Low Carbon, Sustainable Eco-City introduced by the Environmental Protection Bureau, Kaohsiung City Government (2022) stipulated that their goal was to reduce the CO_2 equivalent to 80% of that in 2005 by 2020 and to 50% of that of 2005 by 2050. The CO_2 equivalent of Kaohsiung in 2005 was 65.7325 million metric tons; therefore, this indicated CO_2 equivalents of 52.586 and 32.86625 million metric tons by 2020 and 2050, respectively. Accordingly, arithmetic progression was applied to these mid- and long-term CO_2 equivalent reduction targets to calculate the expected CO_2 equivalent reduction targets for 2020–2050. The CER rates for these years

Table 7. Taipei's total forest carbon sequestration from 2020 to 2050.

Unit: 10,000 metric tons of CO_2.

Year	Forest carbon stock volume of coniferous forests	Forest carbon stock volume of forests with a mix of coniferous and broadleaf trees	Forest carbon stock volume of broadleaf forests	Total forest carbon stock volume	Carbon sequestration
2020	1.96	2.41	216.03	220.40	0.36
2021	1.96	2.41	216.31	220.68	0.28
2022	1.96	2.42	216.62	221.00	0.31
2023	1.97	2.42	216.97	221.36	0.36
2024	1.97	2.43	217.37	221.77	0.41
2025	1.97	2.43	217.81	222.22	0.45
2026	1.98	2.44	218.27	222.68	0.47
2027	1.98	2.44	218.74	223.17	0.48
2028	1.99	2.45	219.23	223.66	0.49
2029	1.99	2.45	219.72	224.16	0.50
2030	2.00	2.46	220.22	224.67	0.51
2031	2.00	2.46	220.72	225.19	0.52
2032	2.01	2.47	221.24	225.71	0.53
2033	2.01	2.47	221.76	226.25	0.54
2034	2.02	2.48	222.30	226.79	0.54
2035	2.02	2.49	222.84	227.35	0.55
2036	2.03	2.49	223.39	227.91	0.56
2037	2.03	2.50	223.95	228.48	0.57
2038	2.04	2.51	224.51	229.05	0.57
2039	2.04	2.51	225.08	229.63	0.58
2040	2.05	2.52	225.65	230.21	0.58
2041	2.05	2.52	226.22	230.79	0.58
2042	2.06	2.53	226.79	231.37	0.58
2043	2.06	2.54	227.36	231.96	0.59
2044	2.07	2.54	227.94	232.55	0.59
2045	2.07	2.55	228.52	233.14	0.59
2046	2.08	2.56	229.11	233.74	0.60
2047	2.08	2.56	229.70	234.34	0.60
2048	2.09	2.57	230.28	234.94	0.60
2049	2.09	2.58	230.87	235.54	0.60
2050	2.10	2.58	231.46	236.14	0.60

were obtained and are shown in Table 5. According to the results, from 2020 to 2050, Taipei and Kaohsiung should decrease their CO_2 equivalent by 5.8633 and 22.9284 million metric tons, respectively.

Carbon Prices

The prices of related items were obtained by referencing relevant sources, as described: (1) The price of CO_2 equivalent was set at $49.08 per metric ton from the Greenhouse Gas Reduction and Management Act (Environmental Protection Administration of Taiwan 2015); (2) the carbon prices of Taiwan, Mainland China, Japan, and the European Union (EU) were set according to those announced by the World Bank (2022) on August 1, 2019; (3) the US dollar–New Taiwan Dollar exchange rate was set at NT$30.56 according to the Bank of Taiwan in 2019; (4) the carbon price of the EU was set at $30.47 per metric ton according to the European Union Emission Trading Scheme; (5) the carbon price of Japan was set at $2.65 per metric ton according to the Japan carbon tax; and (6) the carbon price of Mainland China was set at $12.16 per metric ton according to the Beijing pilot emissions trading scheme. The carbon prices of Taiwan, Mainland China, Japan, and the EU are provided in Table 6.

Carbon Offsets

The carbon sequestration calculation formulas released by the IPCC (2006) and the total forest stock volume of Taipei and Kaohsiung were used to calculate their expected annual forest carbon stock volume for 2020–2050. Subsequently, the annual forest carbon sequestration increments for the cities were calculated and used as their carbon offsets (P). Then, forest stock volume for 2020–2050 obtained using equation (4) was used to calculate their forest carbon sequestration volume (see Tables 7 and 8). The results suggested that, overall, Taipei's forest carbon sequestration volume was lower than that of Kaohsiung; however, Taipei's carbon sequestration increments were higher than those of Kaohsiung. In future trend predictions, because Kaohsiung's forest stock

Table 8. Kaohsiung's total forest carbon sequestration from 2020 to 2050.

Unit: 10,000 metric tons of CO_2					
Year	Forest carbon stock volume of coniferous forests	Forest carbon stock volume of forests with a mix of coniferous and broadleaf trees	Forest carbon stock volume of broadleaf forests	Total forest carbon stock volume	Carbon sequestration
2020	1,212.65	536.61	3,675.35	5,424.61	-3.19
2021	1,212.08	536.36	3,673.63	5,422.08	-2.54
2022	1,211.45	536.08	3,671.70	5,419.23	-2.85
2023	1,210.70	535.75	3,669.44	5,415.89	-3.34
2024	1,209.85	535.37	3,666.87	5,412.10	-3.80
2025	1,208.92	534.96	3,664.05	5,407.93	-4.16
2026	1,207.93	534.52	3,661.05	5,403.50	-4.43
2027	1,206.89	534.07	3,657.91	5,398.87	-4.63
2028	1,205.82	533.59	3,654.67	5,394.08	-4.78
2029	1,204.72	533.11	3,651.33	5,389.16	-4.92
2030	1,203.59	532.60	3,647.90	5,384.10	-5.06
2031	1,202.43	532.09	3,644.37	5,378.88	-5.21
2032	1,201.23	531.56	3,640.73	5,373.51	-5.37
2033	1,199.98	531.01	3,636.96	5,367.96	-5.55
2034	1,198.70	530.44	3,633.08	5,362.23	-5.73
2035	1,197.38	529.86	3,629.09	5,356.33	-5.90
2036	1,196.03	529.26	3,624.98	5,350.26	-6.07
2037	1,194.64	528.64	3,620.75	5,344.03	-6.23
2038	1,193.21	528.01	3,616.43	5,337.64	-6.39
2039	1,191.75	527.36	3,612.00	5,331.11	-6.53
2040	1,190.26	526.71	3,607.49	5,324.46	-6.65
2041	1,188.75	526.04	3,602.91	5,317.70	-6.76
2042	1,187.21	525.36	3,598.26	5,310.83	-6.87
2043	1,185.65	524.66	3,593.52	5,303.83	-7.00
2044	1,184.05	523.96	3,588.68	5,296.69	-7.14
2045	1,182.42	523.24	3,583.73	5,289.39	-7.30
2046	1,180.75	522.50	3,578.68	5,281.93	-7.46
2047	1,179.05	521.75	3,573.53	5,274.33	-7.60
2048	1,177.33	520.98	3,568.30	5,266.61	-7.72
2049	1,175.58	520.21	3,563.01	5,258.80	-7.81
2050	1,173.82	519.43	3,557.67	5,250.92	-7.89

Note: When the forest carbon sequestration increment of a region is negative, the region's forest carbon stock volume in the current year is less than that of the previous year.

volume would be lower and lower each year, Kaohsiung's annual forest carbon sequestration increments were negative. Regarding overall forest carbon sequestration growth trends, the forest carbon sequestration of Taipei and Kaohsiung exhibited annual increases and decreases, respectively.

Carbon Trading Volume

Carbon trading volume entails carbon credits (that are available for sale) that must be purchased. It is calculated by subtracting carbon offset from expected carbon emissions target volume. By subtracting the carbon offsets of Taipei and Kaohsiung from their expected carbon emissions target volume for the years 2020–2050, the cities' carbon trading volumes were obtained. Because the cities' annual carbon offsets are generally lower than their expected carbon emissions targets, they must purchase carbon credits from other regions or increase their forest stock volume to compensate for their excess carbon emissions, as shown in Table 9.

Empirical Results

Total CER costs to be expended by Taipei and Kaohsiung in achieving their 2050 CER targets as well as the benefits of carbon offset markets and forest carbon sequestration were examined. To analyze the effects of CER costs on the economy and the environment, three scenarios are discussed: (1) scenario A1: a carbon offset market exists, and forest carbon sequestration can be used as carbon offsets; (2) scenario A2: a carbon offset market exists, but forest carbon sequestration cannot be used as carbon offsets; and (3) scenario B: a carbon offset market does not exist. Tables 10 and 11 show the total CER costs of Taipei and Kaohsiung, respectively, for 2020–2050 in all the scenarios.

Scenario A1

In scenario A1, because the expected carbon emissions targets of both Taipei and Kaohsiung were greater than their carbon offsets, the two cities are required to purchase carbon credits from other regions or increase their forest carbon sequestration volume.

CER costs change when the carbon prices used are changed. The CER costs that are expended by Taipei to achieve its expected 2050 carbon emissions target volume in Scenario A1 are as follows: at a carbon price of $32.47, its CER costs range from $192.99 to 353.85 million; at $12.19, its CER costs range from $108.20 to 146.56 million; and at $2.65, its CER costs range from $68.49 to 42.95 million. The CER costs that are expended by Kaohsiung to achieve its expected 2050 carbon emissions target volume in scenario A1 are as follows: at a carbon price of $32.47, its CER costs range from $1,113.39 to 1,860.39 million; at $12.19, its CER costs range from $444.39 to 725.72 million; and at $2.65, its CER cost is $131.08 million.

When the carbon offsets of a region are greater than carbon emissions target volume, the surplus carbon quota can be sold to other regions as carbon credits to increase their revenues. By contrast, if the carbon emissions target volume of a region is greater than its carbon offsets, it will be required to pay CER costs. To reduce its CER costs, the region may be prompted to implement relevant CER policies.

Scenario A2

If a region considers a carbon offset market but forest carbon sequestration cannot be used as carbon offsets (scenario A2), the expected carbon emissions target volume of this region in the current year is equal to its carbon trading volume. Thus, in scenario A2, the carbon offsets of the region would be zero.

Again, CER costs change when the carbon prices used change. The CER costs that are expended by Taipei to achieve its expected 2050 carbon emissions target volume in scenario A2 are as follows: at a carbon price of $32.47, its CER costs range from $1,648.94 to 425.02 million, and its total CER cost is $11,069.25 million (an increase of $28.18% from scenario A1); at $192.99, its CER costs range from $138.66 to 1,516.20 million, and its total CER cost is $4,853.05 million (an increase of $23.13% from scenario A1); and at $2.65, its CER costs range from $48.92 to 1,454.04 million, and its total CER cost is $1,941.84 million (an increase of $11.40% from scenario A1).

The CER costs that are expended by Kaohsiung to achieve its 2050 expected carbon emissions target volume in scenario A2 are as follows: at a carbon price of $32.47, its CER costs range from $443.43 to 724.71 million, and its total CER cost is $47,384.70 million (a decrease of 0.13% from scenario A1); at $12.19, its CER costs range from $128.44 to 194.27 million, and its total CER cost is $18,255.31 million (a decrease of 0.12% from scenario A1); and at $2.65, its CER costs range from $1,110.83 to 1,857.70 million, and its total CER cost is $4,613.26 million (a decrease of 0.11% from scenario A1). In contrast to Taipei, Kaohsiung has lower CER costs in scenario A2 than those in scenario A1. However, the annual forest carbon sequestration increments of Kaohsiung are negative (Table 8), signifying that in addition to purchasing carbon credits to compensate for its excess carbon emissions, the city must also make up for its decreasing carbon sequestration.

Scenario B

The study also investigated the CER costs of Taipei and Kaohsiung if no carbon offset markets exist to analyze the effects of their absence on total CER costs. The absence of carbon offset markets denotes no carbon prices (i.e., the carbon price is zero).

The annual CER costs of Taipei in scenario B range from $262.37 to 503.72 million, whereas those of Kaohsiung range from $1,660.85 to 2,637.31 million. Comparisons of these figures this those of scenarios A1 and A2 indicate that the CER costs of both Taipei and Kaohsiung are higher in scenario B. At carbon prices of $32.47, 12.19, and 2.65, Taipei's total CER costs in scenario B are 44.19%, 213.41%, and 959.94 % higher than those in scenario A1, respectively, whereas Kaohsiung's total CER costs in scenario B are

Table 9. Carbon trading volume of Taipei and Kaohsiung, 2020 to 2050.

Year	Carbon trading volume (in 10,000 metric tons of CO_2 equivalent)	
	Taipei	Kaohsiung
2020	976.36	5,261.79
2021	954.46	5,195.40
2022	932.52	5,129.98
2023	910.53	5,064.74
2024	888.50	4,999.47
2025	866.43	4,934.10
2026	844.33	4,868.64
2027	822.23	4,803.10
2028	800.11	4,737.52
2029	777.98	4,671.93
2030	755.85	4,606.34
2031	738.99	4,540.76
2032	722.12	4,475.18
2033	705.25	4,409.63
2034	688.36	4,344.07
2035	671.46	4,278.51
2036	654.56	4,212.95
2037	637.65	4,147.38
2038	620.73	4,081.80
2039	603.81	4,016.22
2040	586.89	3,950.60
2041	569.97	3,884.98
2042	553.04	3,819.36
2043	536.11	3,753.75
2044	519.18	3,688.16
2045	502.25	3,622.59
2046	485.31	3,557.01
2047	468.36	3,491.42
2048	451.42	3,425.81
2049	434.48	3,360.17
2050	417.54	3,294.51

Note: If a region's carbon trading volume is positive, the region's expected carbon emissions target volume is greater than its carbon offset, and the region must purchase carbon credits from other regions to compensate for its excess carbon emissions.

Table 10. Taipei's total CER costs for 2020–2050 in all scenarios.

Unit: $1 million							
Year	Scenario A1			Scenario A2			Scenario B
	Carbon price ($/t$CO_2$ e)						
	32.47	12.19	2.65	32.47	12.19	2.65	0.00[a]
2020	341.47	143.20	50.35	413.03	170.01	56.19	503.72
2021	335.39	141.57	50.81	407.04	168.41	56.65	494.00
2022	329.37	140.01	51.33	401.12	166.89	57.19	484.33
2023	323.43	138.53	51.94	395.29	165.45	57.80	474.73
2024	317.55	137.13	52.63	389.55	164.10	58.51	465.20
2025	311.76	135.82	53.42	383.90	162.84	59.31	455.74
2026	306.05	134.60	54.30	378.35	161.68	60.21	446.36
2027	300.45	133.48	55.29	372.90	160.62	61.20	437.08
2028	294.94	132.47	56.38	367.56	159.66	62.30	427.90
2029	289.55	131.57	57.58	362.33	158.83	63.52	418.83
2030	284.28	130.79	58.91	357.22	158.11	64.86	409.88
2031	263.29	113.23	42.95	336.40	140.61	48.92	386.09
2032	258.80	112.16	43.49	332.08	139.61	49.47	378.80
2033	254.36	111.15	44.08	327.81	138.66	50.07	371.55
2034	249.97	110.19	44.73	323.60	137.77	50.74	364.36
2035	245.65	109.30	45.44	319.46	136.94	51.47	357.23
2036	241.39	108.47	46.23	315.38	136.19	52.27	350.16
2037	237.21	107.72	47.08	311.38	135.51	53.14	343.17
2038	233.10	107.05	48.02	307.46	134.90	54.09	336.25
2039	229.08	106.46	49.04	303.63	134.39	55.13	329.42
2040	225.15	105.97	50.16	299.89	133.96	56.26	322.67
2041	221.31	105.57	51.37	296.24	133.64	57.48	316.03
2042	217.59	105.28	52.69	292.70	133.42	58.82	309.49
2043	213.97	105.11	54.12	289.28	133.32	60.27	303.06
2044	210.49	105.06	55.69	285.99	133.34	61.85	296.77
2045	207.14	105.16	57.39	282.84	133.51	63.57	290.61
2046	203.95	105.40	59.25	279.84	133.82	65.44	284.60
2047	200.92	105.81	61.27	277.00	134.31	67.48	278.75
2048	198.07	106.40	63.47	274.35	134.97	69.70	273.09
2049	195.42	107.19	65.88	271.89	135.84	72.12	267.62
2050	192.99	108.20	68.49	269.65	136.92	74.75	262.37
Total	7,934.08	3,650.09	1,643.78	10,225.19	4,508.20	1,830.79	11,439.82

Note: [a]Scenario B considers that there is no carbon offset market, and hence the expected carbon emission target of the city cannot be achieved through carbon offsets. If the emissions exceed the upper bound, carbon taxes (tax-related penalties) must be paid, and the price follows Article 28 of Taiwan's Greenhouse Gas Reduction and Management Act and refers to a monetary penalty of three times the carbon market price per metric ton, with a maximum of $49.08 per metric ton.

50.35%, 290.76%, and 1,456.20% higher than those in scenario A1, respectively.

Discussion

This study mainly analyzes and compares the impact of different carbon prices on the reduction costs of cities with different carbon emissions under the existence and nonexistence of a carbon trading market under the achievement of the 2050 reduction target. From the above results, it is observed that for low-carbon cities (Taipei, the capital of Taiwan), the CER cost is the lowest in the scenario of carbon trading and allowing forest carbon offsets (scenario A1), followed by carbon trading but not allowing forest carbon offsets (scenario A2); the scenario without carbon trading market (scenario B) has the highest CER cost. As the carbon price increases, its CER cost also increases. However, there are some differences in high-carbon-emission cities (Kaohsiung, the largest city in southern Taiwan). The difference between the scenario with carbon trading and forest carbon offsets allowed (scenario A1) and the scenario with carbon trading but forest carbon offsets not allowed (scenario A2) is not remarkable. However, the CER cost is still the highest in the scenario without carbon trading market (scenario B). In addition, cities with different carbon emissions have different CER costs. Kaohsiung (a city with high carbon emissions) has higher CER costs than Taipei

Table 11. Kaohsiung's total CER costs for 2020–2050 in all scenarios.

Unit: $1 million							
Year	Scenario A1			Scenario A2			Scenario B
	Carbon price ($/t$CO_2$ e)						
	32.47	12.19	2.65	32.47	12.19	2.65	0.00[a]
2020	1,762.94	694.46	194.07	1,761.90	694.07	193.98	2,637.31
2021	1,696.62	641.62	147.54	1,695.80	641.31	147.47	2,559.96
2022	1,675.77	634.06	146.20	1,674.85	633.71	146.12	2,528.24
2023	1,655.02	626.55	144.90	1,653.94	626.15	144.81	2,496.65
2024	1,634.30	619.09	143.64	1,633.07	618.63	143.54	2,465.08
2025	1,613.59	611.65	142.42	1,612.24	611.15	142.31	2,433.51
2026	1,592.89	604.24	141.23	1,591.45	603.70	141.12	2,401.93
2027	1,572.19	596.86	140.08	1,570.69	596.29	139.96	2,370.34
2028	1,551.52	589.50	138.97	1,549.97	588.92	138.84	2,338.78
2029	1,530.89	582.19	137.89	1,529.29	581.59	137.76	2,307.24
2030	1,510.29	574.91	136.85	1,508.65	574.29	136.71	2,275.74
2031	1,489.74	567.68	135.85	1,488.05	567.04	135.71	2,244.29
2032	1,469.24	560.49	134.90	1,467.49	559.84	134.76	2,212.90
2033	1,448.79	553.36	134.00	1,446.99	552.68	133.86	2,181.56
2034	1,428.41	546.28	133.16	1,426.55	545.59	133.01	2,150.28
2035	1,408.07	539.26	132.38	1,406.16	538.54	132.22	2,119.05
2036	1,387.80	532.30	131.65	1,385.83	531.57	131.49	2,087.88
2037	1,367.59	525.41	130.99	1,365.57	524.65	130.83	2,056.78
2038	1,347.45	518.59	130.41	1,345.38	517.81	130.24	2,025.74
2039	1,327.39	511.84	129.90	1,325.26	511.04	129.72	1,994.78
2040	1,307.39	505.16	129.46	1,305.23	504.35	129.28	1,963.87
2041	1,287.47	498.57	129.11	1,285.27	497.75	128.93	1,933.05
2042	1,267.64	492.07	128.85	1,265.41	491.23	128.67	1,902.32
2043	1,247.92	485.67	128.68	1,245.64	484.82	128.50	1,871.69
2044	1,228.31	479.37	128.63	1,225.99	478.51	128.44	1,841.18
2045	1,208.82	473.20	128.69	1,206.45	472.31	128.50	1,810.80
2046	1,189.45	467.15	128.88	1,187.03	466.25	128.68	1,780.54
2047	1,170.22	461.24	129.21	1,167.75	460.32	129.00	1,750.40
2048	1,151.13	455.47	129.67	1,148.62	454.53	129.47	1,720.41
2049	1,132.18	449.85	130.30	1,129.64	448.90	130.09	1,690.55
2050	1,113.39	444.39	131.09	1,110.83	443.43	130.88	1,660.85
Total	43,774.40	16,842.49	4,229.58	43,716.97	16,820.98	4,224.89	65,813.70

Note: [a]Scenario B considers that there is no carbon offset market, and hence the expected carbon emission target of the city cannot be achieved through carbon offsets. If the emissions exceed the upper bound, carbon taxes (tax-related penalties) must be paid, and the price follows Article 28 of Taiwan's Greenhouse Gas Reduction and Management Act and refers to a monetary penalty of three times the carbon market price per metric ton, with a maximum of $49.08 per metric ton.

(a city with low carbon emissions), and as the carbon price increases, the difference in CER costs is greater (see Table 12). Carbon emissions in scenario B differ from those in scenarios A1 and A2. In scenario A1, the cities' annual expected carbon emissions are greater than their carbon offsets, and they must purchase carbon credits from other regions to compensate for their excess carbon emissions.

By contrast, in scenario B, despite the cities' annual carbon emissions being greater than their carbon offsets, the absence of carbon offset markets means that carbon prices are zero, and the money originally to be spent purchasing carbon credits from other regions is nonexistent. Therefore, the inability of Taipei and Kaohsiung to use carbon offsets or to reduce their carbon emissions to achieve their expected carbon emissions target volume would result in Article 28 of Taiwan's Greenhouse Gas Reduction and Management Act coming into effect (i.e., a monetary penalty of three times the carbon market price per metric ton, with a maximum of $49.08 per metric ton). This penalty may actually be higher than the CER costs to be expended by the cities. Thus, the presence of carbon offset markets may reduce the CER costs of regions that generate excess carbon emissions. To prevent regions from being charged carbon tax–related penalties (because no sufficient carbon credits are available for purchase on carbon offset markets to counter the regions' excess carbon emissions), regions may reduce their carbon emissions.

Table 12. Ratio of the total CER costs in Kaohsiung to Taipei for 2020–2050 in all scenarios.

Year	Scenario A1			Scenario A2			Scenario B
	Carbon price ($/tCO$_2$ e)						
	32.47	12.19	2.65	32.47	12.19	2.65	0.00[a]
2020	0.17	0.16	0.13	0.14	0.13	0.11	0.17
2021	0.17	0.15	0.09	0.14	0.12	0.09	0.17
2022	0.17	0.15	0.09	0.14	0.12	0.08	0.17
2023	0.17	0.15	0.09	0.14	0.12	0.08	0.17
2024	0.17	0.15	0.09	0.14	0.12	0.08	0.17
2025	0.17	0.15	0.09	0.14	0.12	0.08	0.17
2026	0.17	0.15	0.09	0.14	0.12	0.08	0.18
2027	0.17	0.15	0.08	0.14	0.12	0.07	0.18
2028	0.17	0.15	0.08	0.14	0.12	0.07	0.18
2029	0.17	0.14	0.08	0.14	0.12	0.07	0.18
2030	0.17	0.14	0.08	0.14	0.12	0.07	0.18
2031	0.19	0.16	0.10	0.14	0.13	0.09	0.19
2032	0.19	0.16	0.10	0.14	0.13	0.09	0.19
2033	0.19	0.16	0.10	0.14	0.13	0.09	0.19
2034	0.19	0.16	0.10	0.14	0.13	0.09	0.19
2035	0.19	0.16	0.10	0.14	0.13	0.08	0.19
2036	0.19	0.16	0.09	0.14	0.13	0.08	0.20
2037	0.19	0.16	0.09	0.14	0.13	0.08	0.20
2038	0.19	0.16	0.09	0.14	0.13	0.08	0.20
2039	0.19	0.16	0.09	0.14	0.12	0.08	0.20
2040	0.19	0.16	0.08	0.14	0.12	0.08	0.20
2041	0.19	0.15	0.08	0.14	0.12	0.07	0.20
2042	0.19	0.15	0.08	0.14	0.12	0.07	0.20
2043	0.19	0.15	0.08	0.14	0.12	0.07	0.20
2044	0.19	0.15	0.08	0.14	0.12	0.07	0.20
2045	0.19	0.15	0.07	0.14	0.12	0.07	0.20
2046	0.19	0.14	0.07	0.14	0.11	0.06	0.20
2047	0.19	0.14	0.07	0.14	0.11	0.06	0.21
2048	0.19	0.14	0.07	0.14	0.11	0.06	0.21
2049	0.19	0.14	0.06	0.14	0.11	0.06	0.21
2050	0.19	0.13	0.06	0.13	0.11	0.06	0.21
Total	0.18	0.15	0.08	0.14	0.12	0.08	0.19

Note: [a]Scenario B considers that there is no carbon offset market, and hence the expected carbon emission target of the city cannot be achieved through carbon offsets. If the emissions exceed the upper bound, carbon taxes (tax-related penalties) must be paid, and the price follows Article 28 of Taiwan's Greenhouse Gas Reduction and Management Act and refers to a monetary penalty of three times the carbon market price per metric ton, with a maximum of $49.08 per metric ton.

Therefore, carbon offset markets act to restrict the carbon emissions of regions with high carbon emissions and enable regions with low carbon emissions (i.e., those whose carbon offsets are greater than their carbon emissions) to sell carbon credits, generating revenue and facilitating local development.

Conclusions and Recommendations

The CER targets of Taipei and Kaohsiung for the year 2050 were used to calculate the CER costs required to achieve the targets. The following three scenarios were introduced to assess and analyze the effects of carbon offset markets and forest carbon sequestration on CER costs: (1) scenario A1: a carbon offset market exists, and forest carbon sequestration can be used as carbon offsets; (2) scenario A2: a carbon offset market exists, but forest carbon sequestration cannot be used as carbon offsets; and (3) scenario B: a carbon offset market does not exist.

The analysis indicates that when forest carbon sequestration cannot be used as carbon offsets (scenario A2), Kaohsiung's total CER costs compared with when carbon sequestration can be used as carbon offsets (scenario A1) move in a direction opposite that of Taipei. This is because Kaohsiung's forest carbon stock volume is decreasing annually, which makes its annual forest carbon sequestration increments negative. Therefore, in scenario A1, Kaohsiung has to pay for its diminishing forest carbon stock volume, increasing its CER costs. Thus, to lower its CER costs, Kaohsiung may increase its forest carbon sequestration volume. The CER costs of Taipei in scenario A1 are lower than those in scenario A2, and these costs are expected to decrease from 2020 to 2050. Thus, Taipei should continue implementing policies that could increase its forest carbon sequestration volume and decrease its CER costs.

If a carbon offset market does not exist (scenario B), then if a region's carbon emissions volume is lower than its carbon offsets in the current year, its surplus carbon offsets cannot be sold to other regions as carbon credits. Therefore, the existence of carbon offset markets would provide this type of region with revenue. By contrast, if a region's carbon emissions are higher than its carbon offsets, its CER costs would increase. Thus, carbon offset markets may act to restrict the carbon emissions of regions with high carbon emissions. If such regions continue to increase their carbon emissions, they will need to pay higher CER costs. If no sufficient carbon credits are available for purchase on carbon offset markets, these regions will be charged carbon tax–related penalties. Levels of economic development of counties and cities in Taiwan are uneven. Therefore, the introduction of carbon offset markets can help counties and cities whose economic development are lagging but whose carbon offsets are greater than their carbon emissions, reducing the gap in economic development between them and more economically prosperous areas. These results support those obtained by Lin and Ge (2019).

By performing simulation analyses (i.e., scenarios A1, A2, and B), this study discovered that the opening of carbon offset markets and the use of forest carbon sequestration as carbon offsets may prompt regions to increase their forest stock volume (and thereby their forest carbon sequestration volume) to lower their CER costs. However, achieving CER solely by using forest carbon sequestration is not sufficient. Carbon emissions can be reduced using a higher ratio of renewable and a lower ratio of highly polluting energy, which will help regions reduce their CER costs.

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Conflict of Interest

None declared.

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