Article

Modeling of the Spatial Distribution of Forest Carbon Storage in a Tropical/Subtropical Island With Multiple Ecozones

Ting-Wei Chang , Guan-Fu Chen , Ken-Hui Chang *

Posted Date: 26 June 2023

doi: 10.20944/preprints202306.1776.v1

Keywords: forest management; forest carbon; carbon sequestration; greenhouse gas (GHG); sustainable forestry; inventory; grid modeling

Article

Modeling of the Spatial Distribution of Forest Carbon Storage in a Tropical/Subtropical Island with Multiple Ecozones

Ting-Wei Chang [1], Guan-Fu Chen [2] and Ken-Hui Chang [2,*]

[1] University of Shizuoka, Japan 52-1 Yada, Suruga Dist., Shizuoka 422-8526, Japan
[2] National Yunlin University of Science & Technology, Yunlin, Taiwan 123 University Road, Section 3, Douliu, Yunlin 64002, Taiwan R.O.C.
* Correspondence: ken@airlab.yuntech.edu.tw

Abstract: Visual data on the geographic distribution of carbon storage helps policy maker to formulate countermeasures on global warming. However, Taiwan, as an island showing diversity in climate and topography, had lacked valid visual data in distribution of forest carbon storage between the last to forest surveys (1993-2015). This study established a model to achieve an estimation that capable to demonstrate the distribution of forest carbon storage. This model uses land use, stand morphology, carbon conversion coefficient databases accordingly for 51 types of major forest in Taiwan. An estimation on 2006 was conducted and shows an overall carbon storage of 165.65 Mt C, with forest carbon storage per unit area of 71.56 t C ha^{-1}, where natural forests and plantations respectively contributed of 114.15 Mt C (68.9%) and 51.50 Mt C (31.1%). By assuming no change in land use type, the carbon sequestration from 2006 to 2007 by the 51 forest types was estimated to be 5.21 Mt C yr^{-1} using historical tree growth and mortality rates. The result reflects the reality of the land use status and event of coverage shifting with time by combining to the two forest surveys in Taiwan.

Keywords: forest management; forest carbon; carbon sequestration; greenhouse gas (GHG); sustainable forestry; inventory; grid modeling

1. Introduction

The substantially increased emission of greenhouse gases (GHGs) through human activities has led to higher radiative forcing, resulting in global warming [1]. Although fossil CO_2 emission slightly decreased from 2019 to 2020, the mean annual fossil CO_2 emission amount from 2011 to 2020 increased to a record level of 9.5±0.5 Gt C yr^{-1} [2] The Intergovernmental Panel on Climate Change (IPCC) reported that anthropogenic activities have caused an estimated increase in the global average temperature of approximately 1.0 °C compared with the average pre-industrial era temperature. This value may reach 1.5 °C between 2030 and 2052 if the current emission rates remain unchanged [3]. Warming-induced climate change leads to notable shifts in ecosystems [4–5], increases risk of extinction [6–7], increases frequency of wildfire [8–9], and threatens food production [10–11]. Thus, carbon neutralization is needed to mitigate global warming and its consequences. Schrag [12] proposed three strategies to reduce the net emission of CO_2: reducing the amount of energy the world uses; expanding the use of carbonless/carbon-neutral energy; and capturing the CO_2 and then storing it (i.e., carbon sequestration). Forests account for over 45% of terrestrial carbon storage [13]; the carbon sequestration rate of global forests, including their soil, has been estimated to be 2.4 ± 0.4 Gt C yr^{-1}, making forests the largest terrestrial carbon sink [14]. Due to the significance of forest ecosystem, reforestation, afforestation play a positive role in the modern carbon sequestrating demand [15]; appropriate management of forest and use of forest product can further promote the efficiency of carbon sequestration by forests [16–17]. In contrast, deforestation is deemed as one of the largest sources of anthropogenic carbon emission in nowadays [18]. To optimize the management of forest for carbon sequestration, assessment on forest carbon storage is essential.

The forest carbon storage of Taiwan, an island with a forest coverage rate of over 60%, has been investigated over the past few decades in numerous studies (e.g., [19–24]). Most recently, the total forest growing stock in Taiwan was 502 million m^{-3}, and the forest carbon storage was 206 Mt C according to the 4th Forest Resources Survey (FRS) in Taiwan conducted from 2008 to 2013 [25]. However, on the other hand, visual data on the geographic distribution of forest carbon storage in Taiwan, which is crucial for the publicizing and policymaking, is lacked in the past few decades until 2015. Presently, the distribution map of forest and bamboo carbon storage depicted in the 4th FRS provided by Forest Bureau in is the only available visual information related to forest carbon storage in Taiwan. Since the 3rd FRS, which was finished in 1993 [26], there has been a marked shift in land use and forest distribution due to the promulgation of the Soil and Water Conservation Act in 1993 and the implementation of afforestation incentivization policies aimed at incentivizing afforestation. Thus, the present carbon storage map in the 4th FRS is insufficient to reflect the temporal changes in regional forest carbon storage occurring in Taiwan.

This study aims to establish a grid model capable of output visualized data which uses databases of forest distribution, stock volume equation, ecozone distribution, land use type, biomass-carbon converting coefficients, forest growth rate and mortality rate to simulate forest carbon storage and sequestration rate. Here we used 2006 as the representative year, since the year is approximately the midway between the 3rd and 4th FRSs.

2. Methodology

2.1. Specification of the Grid Carbon Storage and Carbon Sequestration Modelling of Taiwan

The target region is the main island of Taiwan. Taiwan is located at longitude 124°E to 119°E and latitude 21°N to 25°N. To the west of the land is Taiwan Strait, and to the east lies the Pacific Ocean. The total area is approximately 36,000 square kilometers. The main climate is tropical and subtropical, with an average annual temperature of 22.0°C and an average annual rainfall of 2000 mm. The terrain mainly consists of mountains and hills. The highest mountain range is almost 4000m above sea level, and the plains account for about 1/3 of the island. Since 1993, forest coverage has exceeded 2.1 million hectares (58% coverage) and continues to increase. Due to the influence of vertical changes in climate, there are many species of forest trees, including tropical, temperate and boreal species. There are about 4,000 species of forest trees in Taiwan. Based on the database of land use patterns, delineation of ecozones (specified in Section 2.2) has been added in this study to obtain a map of land use distribution and area information. In addition, the stock volume was calculated according to the volume correlation coefficient unique to each land use type, and then the carbon storage amount was estimated using the biological carbon conversion correlation coefficient. Finally, the map and calculation results were combined to obtain the accumulation and carbon storage distribution of the whole grid.

The 2006 forest distribution used in this study is based on the 3rd FRS, CTCI database and was updated with satellite telemetry data from the Center for Space and Remote Sensing Research of National Central University (CSRSR) from 2005 to 2006. In terms of the map resolution, each grid area is 1 square kilometer, and each grid land use type area is accurate to within 1 square meter. In the calculation process, the diameter at breast height (DBH, cm) and stem height (H, m) of each forest types as well as the number of plants in the forest types were entered, and then the appropriate ecozone database for the forest types in the grid was selected according to the ecozone. The appropriate stock volume equation and the conversion coefficient for the forest types were then selected. They were used to calculate the carbon storage per unit area, which was then multiplied by the occupied areas of the corresponding forest types in the grid to calculate the carbon storage of the forest type in the grid. After all of the grids had been estimated, they were combined to obtain the spatial distribution map of carbon storage over Taiwan island.

2.2. Algorithms and Parameters

This study determined 51 forest types based on the Taiwan Ecosystem Process Model (TEPM) land-use database [27,28]. The forest types and their abbreviations are listed in Table 1. The guidelines of IPCC suggest that when estimating forest carbon storage, it should be distinguished to accommodate the different growth conditions of different ecozones [29]. In this study, Taiwan was divided into five ecozones, namely subtropical mountain system, subtropical humid forest, tropical rainforest, tropical dry forest, and tropical moist deciduous. The spatial distribution is shown in Figure 1.

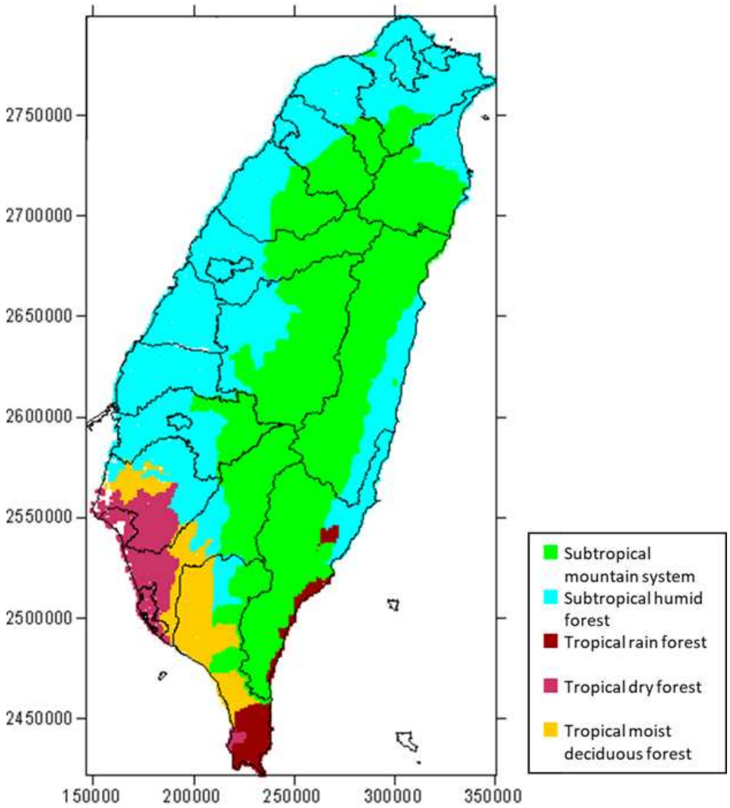

Figure 1. Distribution of the ecozones of Taiwan. Green area represents subtropical mountain system; blue area represents subtropical humid forest; dark brown area represents tropical rainforest; dark pink area represents tropical dry forest; tangerine area represents tropical moist deciduous forest.

Table 1. Abbreviations and areas of the 51 forest types.

Wood type	Regeneration	Forest type	Abbreviation
Coniferous	Nature	Natural Fir Forest	FIR-NF
		Natural Tsuga Forest	TSU-NF
		Natural Cypress Forest	CYP-NF
		Natural Pine Forest	PIN-NF
		Natural Spruce Forest	SPR-NF
		Other Natural Coniferous Forest	O-C-NF
	Plantation	Cypress Plantation	CYP-P
		Pine Plantation	PIN-P
		Luanta Fir Plantation	LF-P
		Taiwania Plantation	TAI-P
		Japanese Cedar Plantation	JC-P
		Taiwan Incense Cedar Plantation	TIC-P
		Other Conifer Plantation	O-C-P

		Mixed Conifer Plantation	MC-P
		Private Coniferous Plantation	P-C-P
		Newly added Coniferous Plantation	NEW-C-P
Broadleaved	Nature	Natural Broadleaved Forest	B-NF
		Natural Mixed Broadleaved Forest	MB-NF
	Plantation	Acacia Plantation	ACA-P
		Sweet Gum Plantation	SG-P
		Camphor Plantation	CAM-P
		Ash Plantation	ASH-P
		Japanese elm Plantation	JE-P
		Sapphire Dragon Tree Plantation	SDT-P
		Other Broadleaved Plantation	O-B-P
		Mixed Broadleaved Plantation	MB-P
		Private Broadleaved Plantation	P-B-P
		Newly added Broadleaved Plantation	NEW-B-P
Bamboo	Nature	Natural Makino Bamboo Forest	MAK-BAM-NF
		Natural Moso Bamboo Forest	MOS-BAM-NF
		Natural Taiwan Giant Bamboo Forest	TG-BAM-NF
		Natural Thorny Bamboo Forest	THO-BAM-NF
		Natural Bambusa Forest	BAM-BAM-NF
		Natural Fargesia Forest	FAR-BAM-NF
		Other Natural Bamboo Forest	O-BAM-NF
	Plantation	Makino Bamboo Plantation	MAK-BAM-P
		Moso Bamboo Plantation	MOS-BAM-P
		Taiwan Giant Bamboo Plantation	TG-BAM-P
		Thorny Bamboo Plantation	THO-BAM-P
		Bambusa Plantation	BAM-BAM-P
		Other Bamboo Plantation	O-BAM-P
		Private Bamboo Plantation	P-BAM-P
Mixed	Nature	Natural Coniferous and Broadleaved Mixed Forest	M-CB-NF
		Natural Bamboo and Coniferous Mixed Forest	M-BAMC-NF
		Natural Bamboo and Broadleaved Mixed Forest	M-BAMB-NF
		Natural Bamboo, Coniferous and Broadleaved Mixed Forest	M-BAMCB-NF
	Plantation	Coniferous and Broadleaved Mixed Plantation	M-CB-P
		Bamboo and Coniferous Mixed Plantation	M-BAMC-P
		Bamboo and Broadleaved Mixed Plantation	M-BAMB-P
		Bamboo, Coniferous and Broadleaved Mixed Plantation	M-BAMCB-P
		Private Coniferous and Broadleaved Mixed Plantation	P-M-CB-P

This study does not consider forest losses caused by logging, fuelwood harvesting, pests and diseases, fires, and so on. Only the living forest storage amount is considered. The general-purpose forest living carbon storage formula suggested in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [29] is as follows:

$$C = A \times V_{stand} \times BCEF \times (1+R) \times CF \quad (1)$$

where C is the mass of carbon contained in biomass (Mt C), A is the coverage area (ha), V_{stand} is the growing stock volume of tree trunk ($m^3\ ha^{-1}$), $BCEF$ is the biomass conversion and expansion factor for expansion of growing stock volume to above-ground biomass ($t\ C\ m^{-3}$), R is the ratio of below-ground biomass to above-ground biomass ($t\ t^{-1}$), and CF is the carbon fraction of dry biomass ($t\ C\ t^{-1}$).

However, at present, database of *BCEF* and assessments of below-ground variables are not adequate in Taiwan. Therefore, in most of this research, only the above-ground biomass is calculated.

The below-ground biomass is only estimated for some species. The calculation formula adopts the estimation formula of Lee et al. [30]:

$$C = A \times V_{\text{stand}} \times EF \times D \times CF \quad (2)$$

where EF is the above-ground biological expansion factor (unit-free), D is the basic wood density (t m^{-3}), and CF is the carbon fraction. Carbon storage per unit area (C_A, t C ha^{-1}) is defined as follows:

$$C_A = C \div A \times 10^6 = V_{\text{stand}} \times EF \times D \times CF \times 10^6 \quad (3)$$

V_{stand} is calculated as follows:

$$V_{\text{stand}} = N \times V_{\text{stem}}\ (DBH, H) \quad (4)$$

where N (stem ha^{-1}) is the stand density of each forest type; V_{stem} (m^3 stem^{-1}) is the growing stock volume, which is calculated from *DBH* and *H* with the stock volume equation of each forest type.

EF, *D*, *CF*, and the volume formulas used for each forest types in this study uses the corresponding parameters to the referred plant species showed in Table S2. Forest types which are comprised of multiple referred plant species use parameters multiplied by the respective weights of each species. Stock volume equation of each plant species at different ecozones are shown in Table S1. The cypress plantation (CYP-P) takes *Chamaecyparis taiwanensis* as the reference species, because it is the main afforestation cypress species in Taiwan. On the other hand, the natural cypress forest (CYP-NF) is mainly a mixture of *C. taiwanensis* and *Chamaecyparis formosensis*, and thus, CYP-NF is assigned with a weight of 0.5 each for the two species. About the pine species, *Pinus massoniana* was taken as the reference species of the pine plantation (PIN-P) because it is introduced as the main afforestation pine species in Taiwan; *Pinus taiwanensis* was taken as the reference species of the nature pine forest (PIN-NF). With respect to forest composition, natural coniferous and broadleaved mixed forest (M-CB-NF) is mainly composed of coniferous and broadleaved forest, with coniferous tree species predominating, including *Chamaecyparis* spp.. Therefore, the coniferous forest part of this forest is mixed with other tree species, including needles, red cypress, cypress, and other broad-leaved trees, each with a weight of 0.25. In the forest types with no specific species, such as other natural coniferous forest (O-C-NF), natural coniferous and broadleaved mixed forest (M-CB-NF), natural mixed broadleaved forest (MB-NF), natural broadleaved forest (B-NF), other conifer plantation (O-C-P), mixed conifer plantation (MC-P), coniferous and broadleaved mixed plantation (M-CB-P), mixed broadleaved plantation (MB-P), and private plantations (i.e., P-C-P, P-B-P, P-BAM-P, and P-M-CB-P), their reference species was assigned as "Mixed Conifer" or "Mixed Broadleaf", whose *D* and *CF* were the averaged value of those of all corresponded species. *D* and *CF* of *Abies kawakamii* and *C. taiwanensis* were the averaged value of those of all the coniferous species in Lin et al [31]; *D* and *CF* of *Liquidambar formosana* and *Paulownia kawakamii* were the averaged value of those of all the broadleaved species in Lin et al [31]. All bamboo forest types, *EF*, *D*, *CF* and volume formulas are all based on the data of *Phyllostachys makinoi* [32].

DBH, *H*, *N* and *A* of each forest type are demonstrated in Table S3. These parameters are mainly obtained from the database of permanent forest plots in 2001. The *DBH*, *H*, *N* of most of the bamboo forest types were obtained from data for *P. makinoi* except *Phyllostachys pubescens* (moso bamboo) forest types (i.e., MOS-BAM-NF and MOS-BAM-P) and *Dendrocalamus latiflorus* (Taiwan giant bamboo) forests (i.e., TG-BAM-NF and TG-BAM-P). For mixed forest types that includes bamboo forest, the weight of bamboo is 0.5, and the weight of the other species evenly shares the other 0.5. In this case, the *DBH* and *H* of the other species were the averaged data of the corresponding forest types.

In this study, we estimated the carbon sequestration for one year, from 2006 to 2007. Assuming that there was no significant change in forest area from 2006 to 2007, the forest carbon storage in 2007 can be estimated based on the annual growth rate and mortality rate, and the change in forest carbon storage between the two years is the annual carbon sequestration (ΔC, Mt C yr^{-1}). The estimation formula is as follows:

$$\Delta C = C_{\text{next}} - C \quad (5)$$

where C_{next} (Mt C) is the carbon storage in the next year. It is defined as follow:

$$C_{next} = A \times V_{stand} \times (1 + G) \times (1 - M) \times BEF \times D \times CF \quad (6)$$

where G (%) is the growth rate of the growing stock volume, and M (%) is the mortality rate of trees in a stand. The annual growth and death rate of each forest type were obtained from a survey on the growth and death of forest resources in Taiwan [33] (Table S4). According to Equations (2), (4) and (5) we can obtain:

$$\Delta C = C \times (1 + G) \times (1 - M) \quad (7)$$

The carbon sequestration per unit area (ΔC_A, t C ha^{-1} yr^{-1}) is calculated as follow:

$$\Delta C_A = \Delta C \div A \times (1 + G) \times (1 - M) \quad (8)$$

2.3. Model Uncertainty Analysis

This study uses Monte Carlo method to estimate the uncertainty of the carbon storage modeling caused by the variation in *DBH* and *H* of the 26 state-owned forest types (i.e., FIR-NF, TSU-NF, CYP-NF, PIN-NF, SPR-NF, O-C-NF, CYP-P, PIN-P, LF-P, TAI-P, JC-P, TIC-P, O-C-P, MC-P, B-NF, MB-NF, ACA-P, SG-P, CAM-P, ASH-P, JE-P, SDT-P, O-B-P, MB-P, M-CB-NF, M-CB-P), whereas those of the newly added forest types (i.e., NEW-C-P and NEW-B-P), private forest types, bamboo forest types, and mixed forest types with bamboo remained fixed. First, we established the normal distribution of *DBH* and *H* basing on the standard deviation of the *DBH* and *H* database for each forest types. Then, we simulated *DBH* and *H* basing on the established normal distribution (regarding *DBH* and *H* are independent of each other) and calculated the carbon storage, repeat for 10,000 times. Finally, the two-tailed 95% confidence interval for the 10,000 simulation results, that is, the upper 2.5th ($C_{2.5}$, Mt C) and 97.5th percentile ($C_{97.5}$, Mt C) values, were used as the error range. The relative carbon storage of the 2.5th ($R_{2.5}$, %) and 97.5th percentile ($R_{97.5}$, %) was defined as follows:

$$R_{2.5} = [(C_{2.5} - C) / C] \times 100\% \quad (8)$$

$$R_{97.5} = [(C_{97.5} - C) / C] \times 100\% \quad (10)$$

3. Results

3.1. Estimation of Forest Carbon Storage

Estimation result of stock volume distribution in Taiwan is shown in Figure 2. The total V_{stand} was 499,448,000 m^3, and the average V_A was 216 m^3 ha^{-1}. Among them, coniferous and broadleaved forests occupied a value of 481,731,000 m^3, with an average V_A of 227 m^3 ha^{-1}; bamboo forests occupied 17,717,000 m^3, with an average V_A of 91 m^3 ha^{-1}. Most of the grids with large stock volume were distributed in the mountainous area at the center and the northern-east part of Taiwan, with altitude of approximately 2500 to 3000 m, despite that some fault zones showed low or no stock. In contrast, plains at eastern sides did not have notable forest stock, only some sparse distribution at the coastal zone.

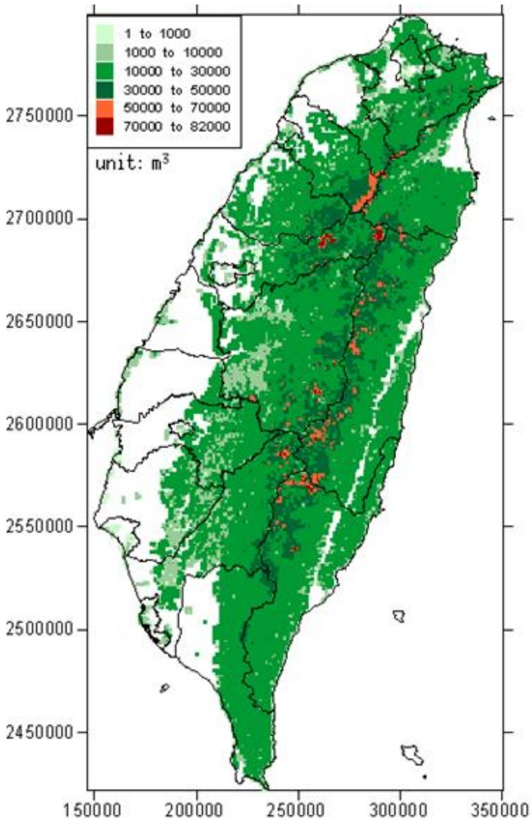

Figure 2. Spatial distribution of V_{stand} according to the 51 forest types in Taiwan. Different colors represent different class intervals of stock volume in each grid.

The estimation result of carbon stock in respective of the 51 forest types are shown in Table 2. The spatial distribution of carbon stock in regardless of forest type is demonstrated in Figure 3. The overall carbon storage amount of the 51 forest types was estimated as 165.65 Mt C in Taiwan. Among them, the carbon storage contributed by the natural forests was 114.15 Mt C (68.9%), whereas the plantations contributed 51.50 Mt C (31.1%), with a ratio of about 7:3. The total carbon storage in the broadleaved forests was 86.75 Mt C (52.4%), followed by coniferous forests with 39.65 Mt C (23.9%); mixed forests, excluding bamboo, with 31.97 Mt C (19.3%); and bamboo and mixed bamboo forests with 7.29 Mt C (4.4%). Among all the forest types, natural broadleaved mixed forest (MB-NF) exhibited the largest carbon storage of 51.79 Mt C. The forest types of natural coniferous had averagely higher values in carbon storage per unit area. Among them, natural spruce forest (SPR-NF) had the highest value of 221.48 t C ha^{-1}. The range of carbon storage per unit area of pure bamboo forests was between 16-70 t C ha^{-1}, but most of them were less than 30 t ha^{-1}. Only TG-BAM-NF and TG-BAM-P exhibited higher values of 69.59 and 69.99 t C ha^{-1}, respectively.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 June 2023 doi:10.20944/preprints202306.1776.v1

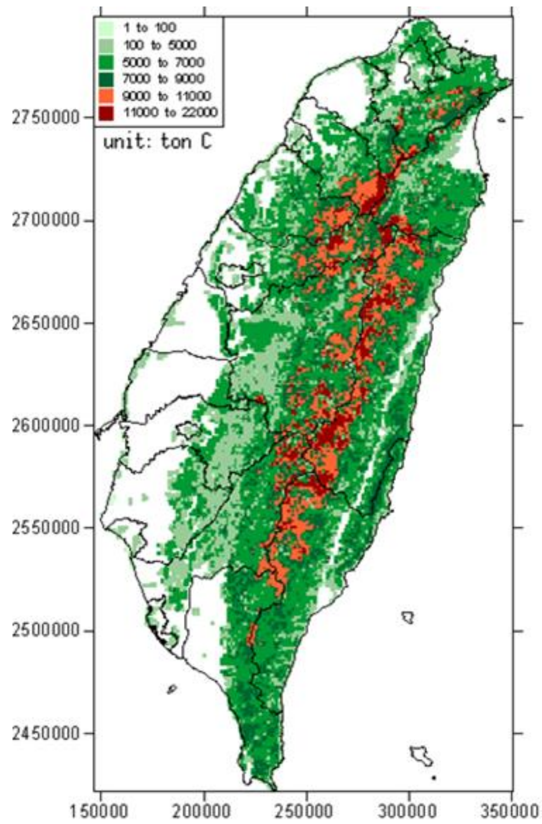

Figure 3. Spatial distribution of forest carbon stock in Taiwan. Different colors represent different class intervals of carbon storage in each grid.

Table 2 Carbon storage amount per area (C_A), carbon storage amount (C), and proportion to total of 51 forest types.

Wood type	Regeneration	Forest type	C_A (t ha^{-1})	C (Mt C)	Proportion to total (%)
Coniferous	Nature	FIR-NF	47.17	1.01	0.6
		TSU-NF	98.94	5.34	3.2
		CYP-NF	149.94	7.39	4.5
		PIN-NF	107.41	7.55	4.6
		SPR-NF	221.48	1.57	0.9
		O-C-NF	210.12	4.87	2.9
		Average or Total	123.03	27.73	16.7
	Plantation	CYP-P	34.97	0.88	0.5
		PIN-P	67.28	3.11	1.9
		LF-P	74.08	2.24	1.4
		TAI-P	43.56	0.22	0.1
		JC-P	37.79	1.78	1.1
		TIC-P	78.38	0.10	0.1
		O-C-P	115.97	0.20	0.1
		MC-P	67.85	3.05	1.8
		P-C-P	79.64	0.32	0.2
		NEW-C-P	78.52	0.02	<0.05
		Average or Total	57.87	11.92	7.2
	Average or Total		91.92	39.65	23.9
Broadleaved	Nature	B-NF	51.78	0.81	0.5
		MB-NF	71.80	51.79	31.3

		Average or Total	71.38	52.60	31.8
	Plantation	ACA-P	81.06	2.97	1.8
		SG-P	35.61	0.15	0.1
		CAM-P	34.42	0.20	0.1
		ASH-P	54.04	0.72	0.4
		JE-P	7.10	0.04	<0.05
		SDT-P	53.88	0.45	0.3
		O-B-P	66.31	0.92	0.6
		MB-P	59.31	1.55	0.9
		P-B-P	53.88	26.98	16.3
		NEW-B-P	50.53	0.17	0.1
		Average or Total	55.26	34.15	20.6
	Average or Total		64.02	86.75	52.4
Bamboo	Nature	MAK-BAM-NF	18.82	0.19	0.1
		MOS-BAM-NF	26.77	0.05	<0.05
		TG-BAM-NF	69.59	0.72	0.4
		THO-BAM-NF	18.67	0.04	0.0
		BAM-BAM-NF	20.36	<0.005	<0.05
		O-BAM-NF	12.96	<0.005	<0.05
		FAR-BAM-NF	18.73	0.34	0.2
		Average or Total	31.33	1.36	0.8
	Plantation	MAK-BAM-P	18.85	0.15	0.1
		MOS-BAM-P	26.29	0.08	<0.05
		TG-BAM-P	69.99	0.52	0.3
		THO-BAM-P	18.70	0.22	0.1
		BAM-BAM-P	19.66	0.02	<0.05
		O-BAM-P	16.52	0.01	<0.05
		P-BAM-P	18.72	0.41	0.2
		Average or Total	26.24	1.41	0.8
	Average or Total		28.51	2.76	1.7
Mixed	Nature	M-CB-NF	100.20	29.47	17.8
		M-BAMC-NF	126.17	0.01	<0.05
		M-BAMB-NF	45.86	2.92	1.8
		M-BAMCB-NF	74.86	0.06	<0.05
		Average or Total	90.50	32.46	19.6
	Plantation	M-CB-P	62.99	2.49	1.5
		M-BAMC-P	48.04	0.10	0.1
		M-BAMB-P	44.55	1.13	0.7
		M-BAMCB-P	55.43	0.30	0.2
		P-M-CB-P	62.93	0.01	<0.05
		Average or Total	55.53	4.03	2.4
	Average or Total		84.62	36.49	22.0
Average or Total			54.86	165.65	100.0

Average or Total: averaged C_A is shown; summed C is shown; summed proportion to total is shown.

The distribution of the total carbon storage of the 26 forest types output from Monte Carlo simulation results is shown in Figure 4, and the respective results of each forest types are shown in Table 3. According to the 95% confidence interval, the amount ranged from 110.30 to 158.81 Mt C (−16 to 21%) and was slightly positively skewed. Generally, $R_{97.5}$ of the forest types ranged from −75% to −20%; the $R_{2.5}$ ranged from 20% to 80%. FIR-NF exhibited the largest uncertainty, where its $R_{97.5}$ and $R_{2.5}$ were −74% and 78%, respectively. It was followed by the natural tsuga forest (TSU-NF),

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 June 2023 doi:10.20944/preprints202306.1776.v1

which exhibited the range from –56% and 80%. CYP-NF has the smallest uncertainty, ranging from –19% to 30%. The range of the broadleaved forest types were generally within –35% to 55%.

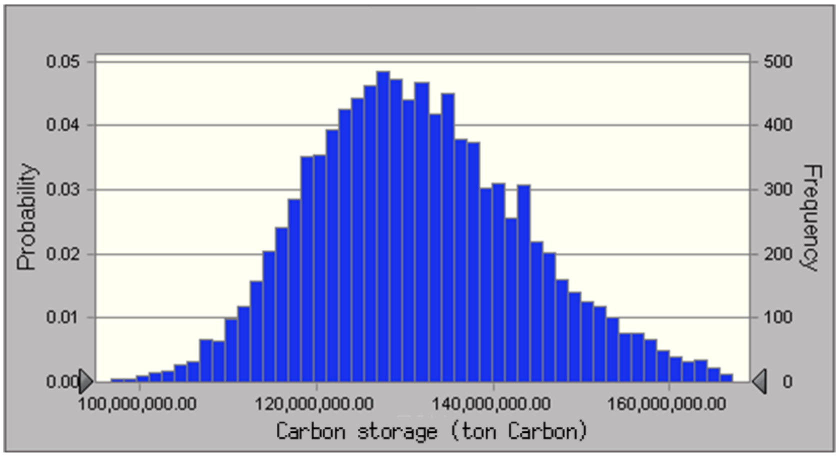

Figure 4. Frequency distribution of the total carbon storage of 26 forest types (n = 10000).

Table 3. Carbon storage and relative carbon storage of 26 forest types at 97.5th and 2.5th percentage in Monte-Carlo simulation (n = 10000).

Forest Type	Carbon Storage (Mt C)		Relative Carbon Storage (%)	
	97.5th	2.5th	97.5th	2.5th
FIR-NF	0.26	1.79	–74	78
TSU-NF	2.33	9.62	–56	80
CYP-NF	6.01	9.60	–19	30
PIN-NF	5.22	10.75	–31	42
SPR-NF	0.73	2.69	–54	72
O-C-NF	3.20	7.19	–34	48
CYP-P	0.60	1.26	–32	43
PIN-P	2.06	4.58	–34	47
LF-P	1.47	3.34	–34	49
TAI-P	0.14	0.32	–35	48
JC-P	1.15	2.64	–35	48
TIC-P	0.07	0.15	–33	51
O-C-P	0.13	0.29	–35	45
MC-P	1.63	3.70	–46	21
B-NF	0.52	1.21	–35	50
MB-NF	33.18	77.95	–36	51
ACA-P	2.11	4.04	–29	36
SG-P	0.10	0.21	–36	43
CAM-P	0.13	0.29	–34	47
ASH-P	0.48	1.06	–34	47
JE-P	0.03	0.06	–34	47
SDT-P	0.29	0.67	–36	49
O-B-P	0.59	1.39	–35	51
MB-P	1.00	2.34	–35	51
M-CB-NF	22.31	40.10	–24	36
M-CB-P	1.63	3.70	–34	49
Total	110.07	159.59	–16	22

 doi:10.20944/preprints202306.1776.v1

3.2. Estimation of Annual Carbon Sequestration from 2006 to 2007

ΔC of each forest type is shown in Table 4. As the result, the total ΔC from 2006 to 2007 in Taiwan was estimated to be 5.21 Mt C yr^{-1}. And the average ΔC_A was 2.26 t C ha^{-1} yr^{-1}. The natural forests contributed about 2.22 Mt C yr^{-1} (42.6%), while that of the plantations was 2.99 Mt C yr^{-1} (57.4%), with a ratio of about 4:6. In terms of wood type, the ΔC of broadleaved forests was 3.46 Mt C yr^{-1} (66.4%), followed by coniferous forests with 0.96 Mt C yr^{-1} (18.4%); other mixed forests with 0.45 Mt C yr^{-1} (8.7%); and bamboo forests and mixed bamboo forests with 0.34 Mt C yr^{-1} (6.5%). Among the forest types, ΔC of the private broadleaved plantation (P-B-P) reached to 1.73 Mt C yr^{-1}, accounting for 41.9% of total forest carbon sequestration in the simulation.

Table 4. Annual carbon sequestration amount per area (ΔC_A), annual carbon sequestration amount (ΔC), and proportion to total of 51 forest types.

Wood Type	Regeneration	Forest Type	ΔC_A (t C ha^{-1} yr^{-1})	ΔC (Mt C yr^{-1})	Proportion to Total (%)
Coniferous	Nature	FIR-NF	0.40	0.01	0.2
		TSU-NF	0.84	0.05	0.9
		CYP-NF	1.33	0.07	1.3
		PIN-NF	1.28	0.09	1.7
		SPR-NF	1.88	0.01	0.3
		O-C-NF	4.59	0.11	2.0
		Average or Total	0.68	0.33	6.3
	Plantation	CYP-P	1.85	0.05	0.9
		PIN-P	3.56	0.16	3.2
		LF-P	3.91	0.12	2.3
		TAI-P	2.33	0.01	0.2
		JC-P	2.00	0.09	1.8
		TIC-P	4.07	0.01	0.1
		O-C-P	6.22	0.01	0.2
		MC-P	3.59	0.16	3.1
		P-C-P	4.23	0.02	0.3
		NEW-C-P	4.15	<0.005	<0.05
		Average or Total	0.33	0.63	12.1
	Average or Total		0.45	0.96	18.4
Broadleaved	Nature	B-NF	1.22	0.02	0.4
		MB-NF	1.74	1.26	24.1
		Average or Total	0.58	1.27	24.5
	Plantation	ACA-P	5.19	0.19	3.6
		SG-P	2.34	0.01	0.2
		CAM-P	2.20	0.01	0.2
		ASH-P	3.46	0.05	0.9
		JE-P	0.46	<0.005	<0.05
		SDT-P	3.47	0.03	0.6
		O-B-P	4.23	0.06	1.1
		MB-P	3.78	0.10	1.9
		P-B-P	3.44	1.72	33.1
		NEW-B-P	3.23	0.01	0.2
		Average or Total	0.28	2.18	41.9
	Average or Total		0.39	3.46	66.4
Bamboo	Nature	MAK-BAM-NF	0.98	0.01	0.2
		MOS-BAM-NF	1.39	0.00	0.1
		TG-BAM-NF	3.62	0.04	0.7

		THO-BAM-NF	0.97	<0.005	<0.05
		BAM-BAM-NF	1.04	<0.005	<0.05
		O-BAM-NF	0.68	<0.005	<0.05
		FAR-BAM-NF	0.97	0.02	0.3
		Average or Total	0.61	0.07	1.4
	Plantation	MAK-BAM-P	0.98	0.01	0.2
		MOS-BAM-P	1.37	0.00	0.1
		TG-BAM-P	3.64	0.03	0.5
		THO-BAM-P	0.97	0.01	0.2
		BAM-BAM-P	1.02	<0.005	<0.05
		O-BAM-P	0.86	<0.005	<0.05
		P-BAM-P	0.97	0.02	0.4
		Average or Total	0.73	0.07	1.4
	Average or Total		0.68	0.14	2.8
Mixed	Nature	M-CB-NF	1.42	0.42	8.0
		M-BAMC-NF	5.45	<0.005	<0.05
		M-BAMB-NF	1.98	0.13	2.4
		M-BAMCB-NF	3.24	<0.005	<0.05
		Average or Total	0.66	0.55	10.5
	Plantation	M-CB-P	0.89	0.04	0.7
		M-BAMC-P	2.08	<0.005	0.1
		M-BAMB-P	1.93	0.05	0.9
		M-BAMCB-P	2.40	0.01	0.2
		P-M-CB-P	0.89	<0.005	<0.005
		Average or Total	0.71	0.10	2.0
	Average or Total		0.66	0.65	12.5
Average or Total			0.44	5.21	100.0

Average or Total: averaged ΔC_A is shown; summed ΔC is shown; summed proportion to total is shown.

4. Discussion

4.1. Estimation of Forest Carbon Distribution in Taiwan

Our estimation of carbon storage of Taiwan's 51 forest types in 2006 showed a total value of 165.6 Mt C, and the forest carbon storage per unit area was 71.56 t C ha^{-1}. This is approximately the same as the world average of carbon stored in above-ground and below-ground biomass (72.6 t C ha^{-1}) and surpasses the Asian average (60.3 t C ha^{-1}) [34]. However, the below-ground carbon of partial species in were not included in our estimation, thus, the actual amount is expected to be higher. Evaluation studies on forest carbon storage during 1993 to 2014 in Taiwan usually ignored the bamboo forest and private forest. Here if we exclude the storage of bamboo forests, private forests and newly added forest from our estimation, the 95% confident range of forest carbon storage is 110.07–159.59 Mt C in 2006. While Chiou et al. [22] used the 3rd FRS data and SPOT satellite imagery in 2004 to estimate the carbon storage of state-owned coniferous and broadleaved forests in Taiwan and came out with much higher results than our estimation, where the storage ranges from 146 to 261 Mt C when using the local parameters. and ranges from 161 to 286 Mt C when using IPCC recommended parameters. Wang [24] estimated that the carbon storage of state-owned coniferous and broadleaved forests in Taiwan in 2006 was 137.27 Mt C, and the average carbon storage per unit area was 99.52 t ha^{-1}, which was similar to the results of this study. Generally, our estimation of forest carbon stock in 2006 is within a reasonable bound to previous evaluations studies.

By simulating spatial distribution of forest carbon storage, there was a high C_A in high regions with altitude of 2500 to 3500 m (123.03 t C ha^{-1}), which can be attributed to natural coniferous forest types including CYP-NF, PIN-NF, SPR-NF, and other natural coniferous forest (O-C-NF). This correctly reflected the natural coniferous forests in the center mountains of Taiwan, where the forests are showing old-growth features and with enriched volume stock. Among them, FIR-NF showed much lower C_A than other natural coniferous types and a large variation in the uncertainty test, it might be not a misestimation because the *DBH* and *H* database used in the simulations are from permanent plots and can therefore be considered close to the real condition. In fact, the distribution of fir forests is at an altitude range of 3100-3600m, which is much higher than that of other pure coniferous forest types, and tall fir trees are easily broken due to strong mountain winds, resulting in a smaller wood stock [35,36]. Thus, the larger variation of FIR-NF was more likely due to its nature of wide variability of *DBH* and *H*. In addition, C_A of coniferous plantations in the simulation was much smaller than that of natural coniferous forests (57.87 t C ha^{-1}). This correctly reflects the status of coniferous plantation, where the stand age is much younger than that of natural forests in Taiwan. The estimated distribution also demonstrates that forest regions at lower altitudes (<1500 m) showing generally lower C_A (64.02 t C ha^{-1}). This is reasonable because that these regions were mainly occupied by broadleaved forests. These broadleaved forests were mostly secondary forest, which have lower stock volumes in compared to coniferous forests. Although the lower C_A broadleaved forests occupied three times more total coverage area than the coniferous forests did. Thus, our simulation showed a larger total carbon storage of the broadleaved forest types than that of the coniferous forest types. However, the simulated carbon storage of broadleaved forests was mostly contributed by MB-NF and P-B-P, whose composition of species were not specifically defined, and the parameters were roughly defined with the averaged value of other corresponding forest types. Thus, our simulation may only reflect the characteristics of carbon storage distribution of broadleaved forest in a low resolution. Also, On the other hand, the low C_A of JE-P in the simulation was attributed to the low *H* and *N* in the database, which reflected the typical wide crown and short stem of Japanese elm in reality.

Although bamboo forest only contribute a low proportion of forest coverage, in the context of global warming, the habitat of coniferous forests may decrease, and bamboo forest may expand to replace the coniferous forests according to vegetation habitat simulations [37,38]. With regard to the increasing importance of them, this we included the bamboo forests bamboo-mixed forests into our estimation. It is demonstrated that the low C_A and the low coverage area resulting in a contribution less than 5% of the forest carbon storage. In the calculation of the most of bamboo species, we used the parameters of *P. makinoi*. However, the rhizome system of bamboo species can be divided into two types: pachymorph (clumped) and leptomorph (scattered) [39]. The shape of the culm and the distribution pattern in a plot are considerably different between the two types, and thus, it may not correctly reflect the actual growth of the clump bamboo forest. Our result is very close to that of the simulation by Lin [23], in which bamboo and mixed bamboo forests had a carbon storage of 6 Mt C. A more recent study of Yen et al. [40] estimated the bamboo carbon storage per unit area with a value of 49.81 t C ha^{-1}, which was much higher than our result. Due to the discrepancy, further investigation on carbon storing characteristic of bamboo species is suggested to give a more definite inventory of the bamboo carbon storage in Taiwan.

4.2. Carbon Sequestration Simulation Results

The forest stock volume of Taiwan has constantly increased from 1993 to 2015 [25]. According to in 3rd FRS, the total forest stock volume of coniferous and broadleaved forests was estimated to be 358,209,000 m^3, and the stock volume per unit area was estimated to be 184 m^3 ha^{-1} in 1993 [26]. The 4th FRS reported that in 2015, the total stock volume of coniferous and broad-leaved forest was 494,016,000 m^3, and the volume per unit area was approximately 255 m^3 ha^{-1}. Differentiate those of the two FRS, we can see that the total stock volume increased by approximately 135,807,000 m^3, with an average annual increase rate of 6,173,000 m^3. Thus, remarkable carbon sequestrations by forest ecosystems in Taiwan are expected. As the supplementary between the two FRS, we estimated the total stock volume of coniferous and broad-leaved forest to be 411,349,000 m^3 and 255 m^3 ha^{-1} in 2006. From 1993 to 2006, the total stock volume increased by 53,140,000 m^3, and the stock volume per unit area increased by 72 m^3 ha^{-1}. Averagely, the stock volume increased by 4,088,000 m^3 per year, and the stock volume per unit area increased by 5.5 m^3 ha^{-1} per year. From 2006 to 2015, the total stock volume

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 June 2023 doi:10.20944/preprints202306.1776.v1

increased by approximately 82,667,000 m^3, with an average increase rate of 9,185,000 m^3 per year, which is more than two folds that of the value during 2006 to 2015. The stock volume per unit area had no substantial change from 2006 to 2015 according to the estimations, which infers a considerable increase in forest coverage area between 2006 and 2015, and this is consistent with the period of afforestation incentivization of Council of Agriculture.

We estimated the annual carbon sequestration of forests from 2006 to 2007, by assuming no significant change in vegetation distribution, and the change in forest biomass is only attributed to natural death and growth during the period. According to the result, it can be seen that broadleaved forest types accounted for most (3.64 Mt C yr^{-1}, 66.4%) of the total carbon sequestration amount (5.21 Mt C yr^{-1}) in Taiwan's forests. Private forest types, including P-B-P, P-C-P, P-BAM-P, and private coniferous and broadleaved mixed plantation (P-M-CB-P) account for a considerable amount of carbon sequestration, while they were usually omitted in previous studies. If their contributions in carbon sequestration are deducted, the total carbon sequestration of state-owned forests in Taiwan was 3.44 Mt C yr^{-1}. This value is lower than those of Wang [19], Lin et al [21], and Chiou [22], in which annual carbon sequestrated by forests were estimated as 4.74, 4.56, and 3.65-6.90 Mt C yr^{-1}, respectively. The main difference in method of our estimation to other studies are land use database, the parameters of growth and mortality rate, or the parameters related to biomass-carbon conversion. Where Wang [19] used the growth rate conducted by 2nd FRS, and calculation and biomass conversion parameters recommended in Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories [41]; Lin et al. [21] used land use database conducted by the 3rd FRS [26], and simulate the carbon storage with own-conducted biomass-carbon conversion parameters; Chiou et al. [22] respectively used the local parameters and IPCC-recommended parameters to estimate the total carbon sequestration from 1995 to 2006, with consideration of land use change (3.65-6.16 Mt C yr^{-1} and 4.15-6.90 Mt C yr^{-1}, respectively). According to the 4th FRS, forest carbon sequestration in Taiwan was 4.6–5.7 Mt C yr^{-1} from 1993 to 2013, which was close to values reported in other studies and higher than the estimated value of this study. The major reason of the underestimation of this study is the omission of below-ground biomass in the database. Also, the growth rate mortality rate of tree which were conducted in past may be inconformity to the actual status of the stands in 2006. Additionally, the forest distribution had been largely changed from 2006, and our result may not meet the current reality of forestry in Taiwan. Thus, an updating on land use, biomass-carbon conversion, growth rate and mortality rate database is suggested for more accurate estimation that fit current situation in Taiwan.

5. Conclusions

This study established an estimation method that can demonstrate distribution of forest carbon storage in Taiwan, which can facilitate a better legibility for public. To reflect change in tree morphological pattern caused by climate within a species, different stock volume equation was adopted in different ecozones. Our estimation in 2006 determined carbon storage of coniferous, broadleaved, and bamboo forests those are natural or planted. The overall carbon storage amount of the 51 forest types was estimated to be 165.65 Mt C. Our geographic estimation demonstrated that the coniferous forests in the middle and high altitudes have high-density carbon storage, while the broadleaved forests at the middle to low altitudes contribute more than 50% of the carbon storage in forests of Taiwan due to their wide distribution. this estimation reasonably reproduced the forest carbon storage distribution in Taiwan of 2006. A temporal update of the accompanying data also reveals a visual temporal-spatial changes in carbon storage between 2006 and 2007. The annual carbon sequestration by the 51 forest types from 2006 to 2007 in Taiwan was estimated to be 5.21 Mt C yr^{-1}. Generally, this method can provide a detailed visual depiction of Taiwan's forest carbon storage and can be useful for future monitoring of Taiwan's carbon storage distribution.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org., Table S1: Stock volume equation of each plant species respectively at respective ecozones; Table S2: Weighting, above-ground biological expansion factor (*EF*), basic wood density (*D*), and carbon fraction (*CF*) of the referred species of 51 forest type; Table S3: Diameter at breast height (*DBH*), tree height (*H*), stand density (*N*), and coverage area (*A*) of 51 forest types.

Author Contributions: Conceptualization, K.-H. Chang and K.-F. Chen; methodology, K.-F. Chen; software, K.-F. Chen; validation, K.-F. Chen, T.-W Chang and K.-H. Chang; formal analysis, K.-F. Chen and T.-W Chang; investigation, K.-F. Chen and T.-W. Chang; resources, K.-H. Chang; data curation, K.-F. Chen and T.-W. Chang; writing—original draft preparation, T.-W Chang. and K.-F. Chen; writing—review and editing, K.-H. Chang and T.-W. Chang; visualization, T.-W. Chang; supervision, K.-H. Chang; project administration, K.-H. Chang; funding acquisition, K.-H. Chang. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Science and Technology Council, Taiwan (MOST 110-2221-E-224 -015 -MY2; NSC 100-2221-E-224-012-). The APC was funded by National Yunlin University of Science and Technology.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Myhre, G.; Shindell, D.; Bréon, F.-M.; Collins, W.; Fuglestvedt, J.; Huang, J.; Koch, D.; Lamarque, J.-F.; Lee, D.; Mendoza, B.; Nakajima, T.; Robock, A.; Stephens, G.; Takemura, T.; Zhang, H. Anthropogenic and Natural Radiative Forcing. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.
2. Friedlingstein, P.; Jones, M.W.; O'Sullivan, M.; Andrew, R.M.; Bakker, D.C.E.; Hauck, J.; Le Quéré, C.; Peters, G.P.; Peters, W.; Pongratz, J.; Sitch, S.; Canadell, J.G.; Ciais, P.; Jackson, R.B.; Alin, S.R.; Anthoni, P.; Bates, N.R.; Becker, M.; Bellouin, N.; Bopp, L.; Chau, T.T.T.; Chevallier, F.; Chini, L.P.; Cronin, M.; Currie, K.I.; Decharme, B.; Djeutchouang, L.M.; Dou, X.; Evans, W.; Feely, R.A.; Feng, L.; Gasser, T.; Gilfillan, D.; Gkritzalis, T.; Grassi, G.; Gregor, L.; Gruber, N.; Gürses, Ö.; Harris, I.; Houghton, R.A.; Hurtt, G.C.; Iida, Y.; Ilyina, T.; Luijkx, I.T.; Jain, A.; Jones, S.D.; Kato, E.; Kennedy, D.; Klein Goldewijk, K.; Knauer, J.; Korsbakken, J.I.; Körtzinger, A.; Landschützer, P.; Lauvset, S.K.; Lefèvre, N.; Lienert, S.; Liu, J.; Marland, G.; McGuire, P.C.; Melton, J.R.; Munro, D.R.; Nabel, J.E.M.S.; Nakaoka, S.-I.; Niwa, Y.; Ono, T.; Pierrot, D.; Poulter, B.; Rehder, G.; Resplandy, L.; Robertson, E.; Rödenbeck, C.; Rosan, T.M.; Schwinger, J.; Schwingshackl, C.; Séférian, R.; Sutton, A.J.; Sweeney, C.; Tanhua, T.; Tans, P.P.; Tian, H.; Tilbrook, B.; Tubiello, F.; van der Werf, G.R.; Vuichard, N.; Wada, C.; Wanninkhof, R.; Watson, A.J.; Willis, D.; Wiltshire, A.J.; Yuan, W.; Yue, C.; Yue, X.; Zaehle, S.; Zeng, J. Global Carbon Budget 2021. *Earth Syst. Sci. Data* **2022**, *14(4)*, 1917–2005. https://doi.org/10.5194/essd-14-1917-2022
3. Allen, M.R., Dube, O.P.; Solecki, W.; Aragón-Durand, F.; Cramer, W.; Humphreys, S.; Kainuma, M.; Kala, J.; Mahowald, N.; Mulugetta, Y.; Perez, R.; Wairiu, M.; Zickfeld, K. Framing and Context. In *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*; Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield T., Eds.; Cambridge University Press, Cambridge, UK and New York, NY, USA, 2018; pp. 49–92. https://doi.org/10.1017/9781009157940.003
4. Greene, C.H.; Pershing, A.J. Climate Drives Sea Change. *Science* **2007**, *315(5815)*, 1084–1085. https://doi.org/10.1126/science.1136495
5. Weiskopf, S.R.; Rubenstein, M.A.; Crozier, L.G.; Gaichas, S.; Griffis, R.; Halofsky, J.E.; Hyde, K.J.W.; Morelli, T.; Morisette, J.T.; Muñoz, R.C.; Pershing, A.J.; Peterson, D.L.; Poudel, R.; Staudinger, M.D.; Sutton-Grier, A.E.; Thompson, L.; Vose, J.; Weltzin, J.F.; Whyte, K. Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Sci. Total Environ.* **2020**, *733*, 137782. https://doi.org/10.1016/j.scitotenv.2020.137782
6. Manes, S.; Costello, M.J.; Beckett, H.; Debnath, A.; Devenish-Nelson, E.; Grey, K.-A.; Jenkins, R.; Khan, T.M.; Kiessling, W.; Krause, C.; Maharaj, S.S.; Midgley, G.F.; Price, J.; Talukdar, G.; Vale, M.M. Endemism increases species' climate change risk in areas of global biodiversity importance. *Biol. Conserv.* **2021**, *257*, 109070. https://doi.org/10.1016/j.biocon.2021.109070
7. Macinnis-Ng, C.; Mcintosh, A.R.; Monks, J.M.; Waipara, N.; White, R.S.A.; Boudjelas, S.; Clark, C.D. Clearwater, M.J.; Curran, T.J.; Dickinson, K.J.M.; Nelson, N.; Perry, G.L.W.; Richardson, S.J.; Stanley, M.C.; Peltzer, D.A. Climate-change impacts exacerbate conservation threats in island systems: New Zealand as a case study. *Front. Ecol. Environ.* 2021, *19(4)*, 216–224. https://doi.org/10.1002/fee.2285

8. Halofsky, J.E.; Peterson, D.L.; Harvey, B.J. Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecol.* **2020**, *16(1)*, 4–16. https://doi.org/10.1186/s42408-019-0062-8
9. Abram, N.J.; Henley, B.J.; Sen Gupta, A. Lippmann, T.J.R.; Clarke, H.; Dowdy, A.J.; Sharples, Jason J.; Nolan, R.H.; Zhang, T.; Wooster, M.J.; Wurtzel, J.B.; Meissner, K.J.; Pitman, A.J.; Ukkola, A.M.; Murphy, B.P.; Tapper, N.J.; Boer, M.M. Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Commun. Earth Environ.* **2021**, *2(1)*, 8. https://doi.org/10.1038/s43247-020-00065-8
10. Kahiluoto, H.; Kaseva, J.; Balek, J.; Olesen, J.E.; Ruiz-Ramos, M.; Gobin, A.; Kersebaum, K.C.; Takáč, J.; Ruget, F.; Ferrise, R.; Bezak, P.; Capellades, G.; Dibari, C.; Mäkinen, H.; Nendel, C.; Ventrella, D.; Rodríguez, A.; Bindi, M.; Trnka, M. Decline in climate resilience of European wheat. *PNAS* **2019**, *116(1)*, 123–128. https://doi.org/10.1073/pnas.1804387115
11. Mukhopadhyay, R.; Sarkar, B.; Jat, H.S.; Sharma, P.C.; Bolan, N.S. Soil salinity under climate change: Challenges for sustainable agriculture and food security. *J. Environ. Manage.* **2021**, *280*, 111736. https://doi.org/10.1016/j.jenvman.2020.111736
12. Schrag, D.P. Preparing to Capture Carbon. *Science* **2007**, *315(5813)*, 812–813. https://doi.org/10.1126/science.1137632
13. Bonan, G.B. Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Science* **2008**, *320(5882)*, 1444–1449. https://doi.org/10.1126/science.1155121
14. Pan, Y.; Birdsey, R.A.; Fang, J.; Houghton, R.; Kauppi, P.E.; Kurz, W.A.; Phillips, O.L.; Shvidenko, A.; Lewis, S.L.; Canadell, J.G.; Ciais, P.; Jackson, R.B.; Pacala, S.W.; McGuire, A.D.; Piao, S.; Rautiainen, A.; Sitch, S.; Hayes, D. A Large and Persistent Carbon Sink in the World's Forests. *Science* **2011**, *333(6045)*, 988–993. https://doi.org/10.1126/science.1201609
15. Pugh, T.A.M.; Lindeskog, M.; Smith, B.; Poulter, B.; Arneth, A.; Haverd, V.; Calle, L. Role of forest regrowth in global carbon sink dynamics. *PNAS* **2019**, *116(10)*, 4382–4387. https://doi.org/10.1073/pnas.1810512116
16. Chiou, C.R.; Yang, S.I. Estimation of the Stand Carrying Capacity of Chinese Fir Plantations In Taiwan. *Taiwan J. For. Sci.* **2019**, *34(4)*, 305-15.
17. Chiou, C.-R.; Lin, J.-C.; Liu, W.-Y. The Carbon Benefit of Thinned Wood for Bioenergy in Taiwan. *Forests* **2019**, *10*, 255. https://doi.org/10.3390/f10030255
18. Fawzy, S.; Osman, A.I.; Doran, J.; Rooney, D.W. Strategies for mitigation of climate change: a review. *Environ. Chem. Lett.* **2020**, 18, 2069–2094. https://doi.org/10.1007/s10311-020-01059-w
19. Wang, L.J. Impact and Adaptation of Climate Change to Taiwan Forestry (In Chinese). In Proceedings of the Symposium on Climate Change Impact Assessment and Coping Strategies, Symposium on Climate Change Impact Assessment and Coping Strategies, Taipei, Taiwan, April 1996.
20. Yang, S.S. Estimation of the capacity of forest carbon dioxide capturing in Taiwan (In Chinese). *Journal of the Biomass Energy Society of China* **1997**, *16(1-2)*, 1-10.
21. Lin, Y.; Lee, K.; Lin, J. Forest Carbon Sink Estimation for Taiwan by Biomass-Volume Relationship Method. *Journal of Experimental Forest of National Taiwan University* **2002a**, *16(2)*, 71–79.
22. Chiou, C.R.; Wang, R.M.; Liang, Y.C. Aspects of Forest Carbon Evaluation in Taiwan (In Chinese). In Proceedings of Conference on Forest Carbon Sequestration, Taipei, Taiwan, December 2006.
23. Lin, J.C. Estimation of Forest Carbon in Taiwan and Discussion on Sources of Uncertainty (In Chinese). In Proceedings of Conference of Carbon Cycling in Taiwan, Taipei, Taiwan, January 2007.
24. Wang, R. A Study on the Estimative Approach of Forest Carbon Sequestration for National Forest Land in Taiwan. Master Thesis, National Taiwan University, Taipei, Taiwan, July 2007. https://doi.org/10.6342/NTU.2007.02780
25. Taiwan Forest Bureau (2015) Report of the Forth Forest Resources Survey. https://www.forest.gov.tw/File.aspx?fno=66716
26. Taiwan Forest Bureau. *The third forest resources and land use inventory in Taiwan*; Taiwan Forest Bureau: Taipei, Taiwan, 1995.
27. Chang, K.H.; Yu, J.Y.; Chen, T.F.; Lin, Y.P. Estimating Taiwan biogenic VOC emission: Leaf energy balance consideration. *Atmos. Environ.* **2009** *43(32)*, 5092–5100. https://doi.org/10.1016/j.atmosenv.2009.06.038
28. Yu, J.Y.; Chang, K.H.; Chen, T.F. Estimation of CO_2 Assimilation and Emission Flux of Vegetation in Subtropical Island – Taiwan. *Aerosol Air Qual. Res.* **2016**, *16(12)*, 3302-3311. https://doi.org/10.4209/aaqr.2016.07.0309
29. IPCC 2006, *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Publisher: IGES, Kanagawa, Japan, 2006.
30. Lee, K.J.; Lin, J.; Chen, L. The Potential of Carbon Sequestration and Its Cost-benefit Analysis for Taiwania Plantations. *Taiwan J. For. Sci.* **2000**, *15(1)*, 115–123. https://doi.org/10.7075/TJFS.200003.0115
31. Lin, Y.; Liu, C.; Lin, J. Measurement of Specific Gravity and Carbon Content of Important Timber Species in Taiwan. *Taiwan J. For. Sci.* **2002b**, *17(3)*, 291–299. https://doi.org/10.7075/TJFS.200209.0291

32. Ji, Y. A Biomass and Carbon Storage of *Phyllostachys makinoi* Plantation in Central Taiwan. Master Thesis, National Chung Hsing University, Taichung, Taiwan, July 2008. https://doi.org/10.6342/NTU.2007.02780
33. Chang, I.-S; Lin, C.-T. *Report of Continuous Investigation on Taiwan's Forest Resources -Growth and Mortality of Taiwan's Forest Resources*; Publisher: Taiwan Forest Bureau, Taipei, Taiwan, 1982.
34. FAO. *Global Forest Resources Assessment 2020: Main report*; Publisher: FAO, Rome, Italy. https://doi.org/10.4060/ca9825en
35. Lin, C.; Li, C.; Zelený, D.; Chytrý, M.; Nakamura, Y.; Chen, M.; Chen, T.; Hsia, Y.; Hsieh, C.; Liu, H.; Wang, J.; Yang, S.; Yeh, C.; Chiou, C. Classification of the High-Mountain Coniferous Forests in Taiwan. *Folia Geobot*. **2012**, *47(4)*, 373–401. https://doi.org/10.1007/s12224-012-9128-y
36. Chiu, C.; Tzeng, H.; Lin, C.; Chang, K.; Liao, M. Spatial Distribution and Climate Warming Impact on *Abies kawakamii* Forest on a Subtropical Island. Plants **2022**, *11(10)*, 1346. https://doi.org/10.3390/plants11101346
37. Hsu, R.C.-C.; Tamis, W.L.M.; Raes, N.; de Snoo, G.R.; Wolf, J.H.D. Oostermeijer, G.; Lin, S. Simulating climate change impacts on forests and associated vascular epiphytes in a subtropical island of East Asia. *Divers. Distrib.* **2012**, *18(4)*, 334–347. https://doi.org/10.1111/j.1472-4642.2011.00819.x
38. Takano, K.T.; Hibino, K.; Numata, A.; Oguro, M.; Aiba, M.; Shiogama, H.; Takayabu, I.; Nakashizuka, T. Detecting latitudinal and altitudinal expansion of invasive bamboo *Phyllostachys edulis* and *Phyllostachys bambusoides* (Poaceae) in Japan to project potential habitats under 1.5°C-4.0°C global warming. *Ecol Evol.* **2017**, *7(23)*, 9848–9859. https://doi.org/10.1002/ece3.3471
39. McClure, F.A. *The Bamboos: A Fresh Perspective*; Harvard University Press: Cambridge, MA and London, United Kingdom, 1966. https://doi.org/10.4159/harvard.9780674428713
40. Yen, T.-M.; Ji, Y.-J.; L.; J.-S. Estimating biomass production and carbon storage for a fast-growing makino bamboo (*Phyllostachys makinoi*) plant based on the diameter distribution model. *For. Ecol. Manag.* **2010**, *260(3)*, 339–44. https://doi.org/10.1016/j.foreco.2010.04.021
41. IPCC. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*; Publisher: UK Meteorological Office, Bracknell, 1996.