Afforestation and Tending Operations Affecting the Carbon Footprint and Renewable Resources at an Artificial Forest in Taiwan

Fang-Chih Chang,[a,]* Chun-Han Ko,[b] and Ming-Jer Tsai [a,b]

Carbon emissions from afforestation and tending operations were studied in this work. Renewable resources from the operations were evaluated in terms of their potential as fuel. New planting operations were found to result in higher energy consumption, biomass, and emissions compared with the tending operations. The greenhouse gas emissions from new planting and afforestation operations for plantation were 405.0 kg CO_2/ha, 50.1 g CH_4/ha, and 27.1 g N_2O/ha, whereas those from the tending operations were 277.7 kg CO_2/ha, 36.3 g CH_4/ha, and 19.0 g N_2O/ha. The major components of the renewable resources from the afforestation and tending operations were C, O, and H, and the contents of N and S were lower than those specified in the regulations by the European Union for refuse-derived fuels. Therefore, the refuse-derived fuel prepared from the renewable resources of the afforestation and tending operations did not cause NOx or SOx pollution. This fuel resulted in zero CO_2 emissions, and it could be used as an alternative fuel for small boilers in the future.

Keywords: Tending; Carbon footprint; Miscellaneous trees; Refuse-derived fuel; Resource recycling

*Contact information: a: The Experimental Forest, College of Bio-Resources and Agriculture, National Taiwan University, Nan-Tou 55750, Taiwan; b: School of Forestry and Resource Conservation, National Taiwan University, Taiwan; *Corresponding author: d90541003@ntu.edu.tw*

INTRODUCTION

The basic principle of sustainable forest management is to maintain the stability of a forest ecosystem and enable it to achieve multi-objective functions. In the context of silviculture strategies, this means the appropriate extension of a forest's rotation period, with tending operations used as a supporting measure. Tending operations include the timely and appropriate thinning of forests to manage and regulate their density and structure, while pruning and vine removal simultaneously produce high-quality, large-diameter wood and conserves soil, water, and biological resources (Ishii *et al.* 2008). The implementation of forest tending operations is divided into non-logging artificial tending and logging-based tending. Non-logging artificial tending involves fertilizing, weeding, vine removal, and intertillage (soil scarifying during seedling growth) to facilitate growth, whereas logging-based tending involves cleaning-cutting (removal of unhealthy wood, stand density adjustment, quality improvement, and material improvement) and thinning (removal of unhealthy wood, stand density adjustment, quality improvement, and increasing income) (Putz *et al.* 2000; Bilic 2010). Thinning is a crucial mid- and late-stage tending measure in forest management (Yen 2015). Research has indicated that thinning can increase the growth space of forest trees, reduce the competition for forest nutrients, and promote the growth of forest trees (Batsaikhan *et al.* 2018). Stand thinning changes root density and activity; reduces canopy density, the leaf area index, the total photosynthesis system, and transpiration; increases pore density; and promotes direct light exposure during the day, and thereby increasing soil temperature (Tang *et al.* 2005; Campbell *et al.* 2009; Pang *et al.* 2013). Thinning can be divided into (1) qualitative thinning, which is further divided into low thinning, high thinning, mechanical thinning (spacing or row thinning), or selective thinning based on the canopy or stem level; and (2) quantitative thinning, whereby the quantity and quality of thinning are determined together with qualitative thinning, and the number of thinned trees is determined by the number of trees, the diameter at breast height, distance between trees, the tree height, and basal area. Numerous studies have focused on the effects of thinning operations on carbon conservation in soils, forest litter decomposition, the conversion of organic matter in soils, and soil respiration, all of which affect the carbon cycle of a forest ecosystem (Fernandez *et al.* 2012; Olajuyigbe *et al.* 2012; Smolander *et al.* 2013). However, these studies did not examine the carbon emissions caused by the afforestation and tending operations.

According to the results of the fourth forest resource investigation, the total forest area in Taiwan is up to 2.197 million ha, and the forest coverage rate is 60.71%. Taiwan only has a timber self-sufficiency rate of 1%, and is thus greatly dependent on imports from other timber-producing countries. Therefore, the Forestry Bureau has initiated the "Strategic Planning of Forestry Economic Revitalization" to raise the self-sufficiency rate of domestic materials to 3%. The bureau has also implemented plans that reward nationwide afforestation and plain area afforestation sites, providing circular economic utilization of all timber through forestry management approaches such as thinning or selective thinning. The development results of artificial afforestation by Taiwan's forestry industry have gradually matured, with the volume of artificial forest reserves being approximately 47.67 million m^3. Thinning operations in forest tending operations can promote forest renewal and establish the value of sustainability using domestic timber resources. By extending the rotation period of forest trees, the volume of timber accumulation and carbon sequestration of forest stands can be increased with appropriate timber and land use. The management model of artificial forests adopts a low-frequency human intervention approach that adjusts forest structure and density, increases species richness, and improves forest stand productivity and biodiversity through mid- and late-stage tending operations such as pruning and thinning. A rich amount of wood resources can be produced from thinning during mid- and late-stage tending operations, and the effective use of such wood resources from thinning can help improve the low domestic self-sufficiency ratio of timber of less than 1%. Additionally, because thinned forests mostly comprise medium- and small-diameter trees, which consist of a relatively high proportion of juvenile trees that are lightweight, soft, and contain numerous nodes, they are subjected to greater restrictions in terms of processing and utilization. Thinned wood, like ordinary wood, possesses natural and variable textures and colors and can adjust to humidity, absorb ultraviolet rays, insulate, and absorb sound. Therefore, innovatively using thinned wood from domestic afforestation can help utilize forest resources and produce high-quality forests. The active promotion of domestic wood and bamboo products by Wang (2015) is in line with the definition of "domestic production and the sales of timber products," which promotes the local production and consumption of regional raw materials, thereby reducing CO_2 emissions because the products have a shorter distance to travel. Therefore, improving the utilization of thinned wood from domestic afforestation is currently a focus of development that conforms to green and environmentally friendly appeals.

Afforestation and tending also produces forestry waste from weeding, vine removal, pruning, and trimming, as well as waste from thinning and processing, all of which are mostly abandoned onsite. Numerous studies have demonstrated that forestry waste is an exceptional biomass and can be used as biofuel (Solino *et al.* 2009; Akyuz and Balaban 2011; Chen *et al.* 2011; Tarelho *et al.* 2011), bioethanol (Regalbuto 2011; Dodic *et al.* 2012; Ko *et al.* 2012a), biodiesel (Dodic *et al.* 2012; Ko *et al.* 2012b; Prakash *et al.* 2013), functional carbon materials (Sevilla *et al.* 2011), and xylose (Ko *et al.* 2013).

As of March 31, 2018, the number of motor vehicles registered in Taiwan totaled 21,746,355, comprising 7,970,145 and 13,776,210 registered cars and motorcycles, respectively. The lubricating oil in the engines of these vehicles needs to be regularly replaced. The proper use of this waste oil, its conversion into renewable energy, the improvement of its recycling potential, and the creation of circular economic value have become crucial environmental topics.

This study first investigated the carbon emissions from afforestation and tending operations to calculate the carbon sequestration of forests. Next, the waste from afforestation and tending operations (miscellaneous trees) was recycled to evaluate its potential for preparing refuse-derived fuels and its possible impact on the environment. Waste engine oil was used as an additive and mixed with miscellaneous wood and granulated to produce miscellaneous wood-derived biomass fuel.

EXPERIMENTAL

Investigating Afforestation and Tending Operations and Recycled Resources

This study investigated afforestation and tending operations (planting/tending) implemented in the artificial experimental forest at National Taiwan University (NTU). The geographical location and forest resource map of the NTU experimental forest are shown in Figs. 1 and 2, respectively. The artificial forest has reached the threshold for newly planted afforestation or mid- and late-stage tending operations. Afforestation and tending can improve poor forest physiognomy and the renewal of unsatisfactory forest stands, as well as improve biodiversity and forest ecosystems, thereby facilitating the absorption of CO_2. In this study, each afforestation and tending treatment (planting/tending) was repeated thrice at six sampled areas (three for planting and three for tending). The size of each area was 0.1 ha (40-m-long, 25-m-wide). Additionally, the afforestation and mid- and late-stage tending areas and emissions also are calculation from 2008 to 2017 at the NTU experimental forest. The biomass of the weeds from the afforestation and tending operations, the amount of recycled resources produced by those operations, and the associated carbon footprint at each sampled area were surveyed. The initial period of afforestation and tending operations was conducted in this study (Table 1). During the first to third years, the newly planted forest required soil preparation, planting, tending, weeding, and replanting. Another 3-year tending operation involving tending and weeding, vine removal, and trimming was implemented at the afforestation site in the fourth to sixth years.

Carbon Footprint Calculation

The carbon emissions from the afforestation and tending operations in this study were calculated according to the emission coefficient by the Intergovernmental Panel on Climate Change (IPCC) and the Bureau of Energy. This involved multiplying the activity data of the emissions sources (fuel consumption, electricity consumption, water consumption, and amount of garbage) with the emissions coefficients (IPCC 2006). The emissions coefficients of CO_2, CH_4, and N_2O were 2.26 kg/L, 8.16 × 10^{-4} kg/L, and 2.61 × 10^{-4} kg/L, respectively.

The distance between the tending site and the Wood Utilization and Practice Factory of the College of Bio-Resources and Agriculture at NTU were used for the transportation distance to calculate the resulting carbon emissions from the forest afforestation and tending processes, serving as a reference for calculating forest carbon sequestration. The data presented are means ± standard deviation. The existence of significant differences in newly planted group and tending group was tested using t-test. A p-value of 0.05 or less was defined as statistically significant.

Refuse-derived Fuel of Renewable Forestry Resources

The renewable forestry resources were exactly the same as the previous study (Lu *et al.* 2017). The renewable forestry resources were ground and sifted for their particles to pass through a 40-in mesh screen, after which they were mixed in proportion with waste engine oil to prepare 2 mm of miscellaneous wood-derived fuel.

The potential of the refuse-derived biofuel was evaluated by analyzing its calorific value, proximate components (water, ash, and combustibles [volatile and fixed carbon]), and element analysis (carbon, hydrogen, oxygen, nitrogen, sulfur, and chlorine). Its calorific value, combustion efficiency, and the emissions of NOx and SOx were then assessed to determine the optimal refuse-derived fuel. The proximate component analysis referenced the Chinese National Standards CNS 10821 (2012), CNS 10822 (2012), CNS 10823 (2012), and CNS 10824 (2012); the elemental analysis was based on NIEA R403.21C (2005), and the dry-basis calorific value was analyzed based on NIEA R214.01C (2005).

Table 1. Characteristics of Newly Planted Forest and the Tending Operation Site

Tending Operations	Newly Planted			Tending		
Serial number	A	B	C	a	b	c
Ground objects	Miscellaneous Wood *Dendrocalamus latiflorus*	*Phyllostachys edulis* Miscellaneous Wood	*Phyllostachys edulis Taiwania cryptomerioides*	*Michelia compressa*	*Fraxinus griffithii*	*Fraxinus griffithii*
Average slope	15° to 30°	20° to 30°	20° to 45°	20°	20° to 45°	20°
Altitude	500 m	840 m	1200 m	600 m	1000 m	800 m
Direction	Southwest	West	Southwest	South	North	North
Distance	12 km	9 km	12 km	8 km	39 km	10 km
Area	2.0 ha	0.5 ha	1.0 ha	1.25 ha	1.44 ha	1.37 ha
Number of trees planted	3000	750	1500	1875	2160	2055
Survey period	1st year	1st year	1st year	4th year	4th year	4th year

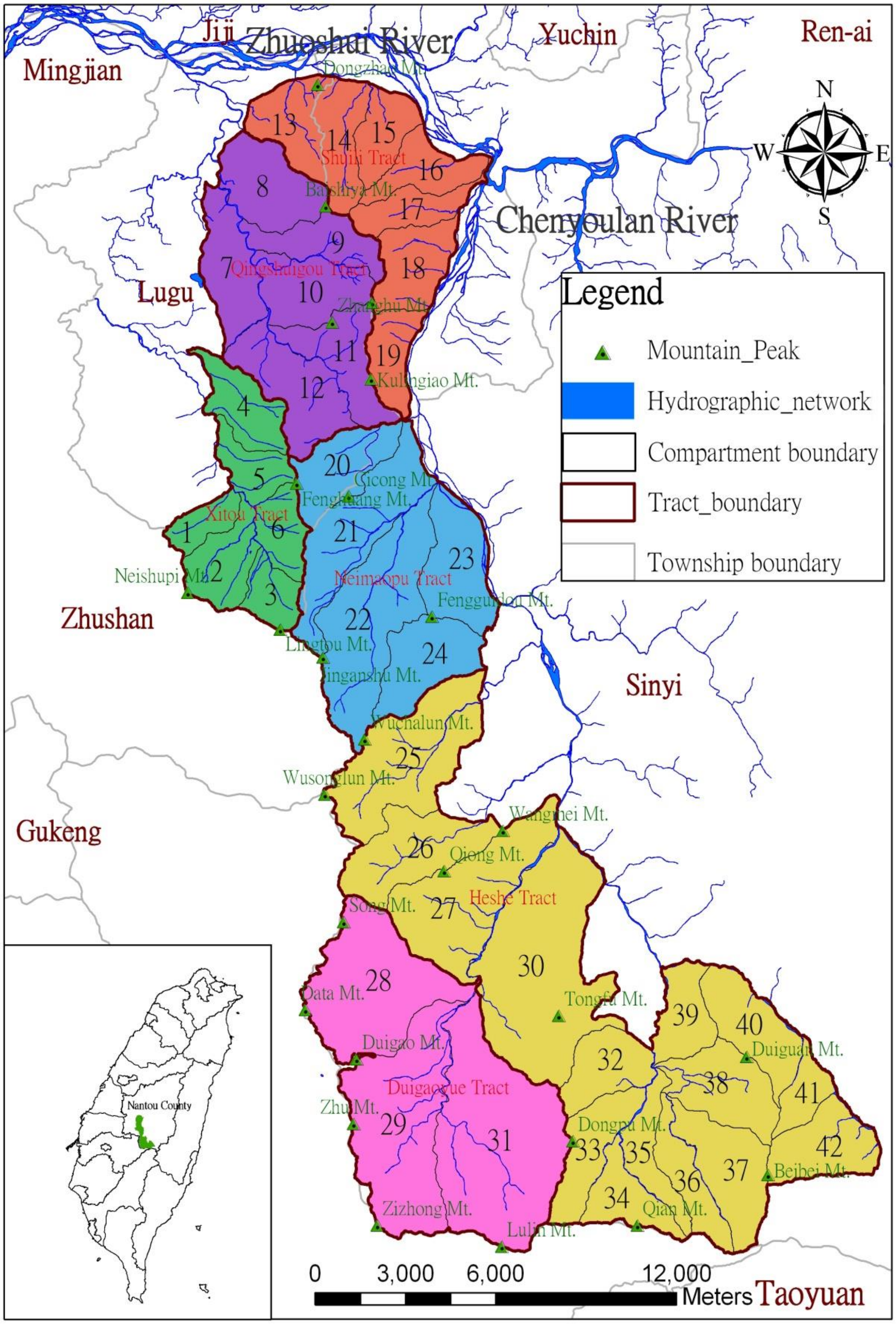

Fig. 1. The geographical location of the NTU experimental forest (Tsai 2018)

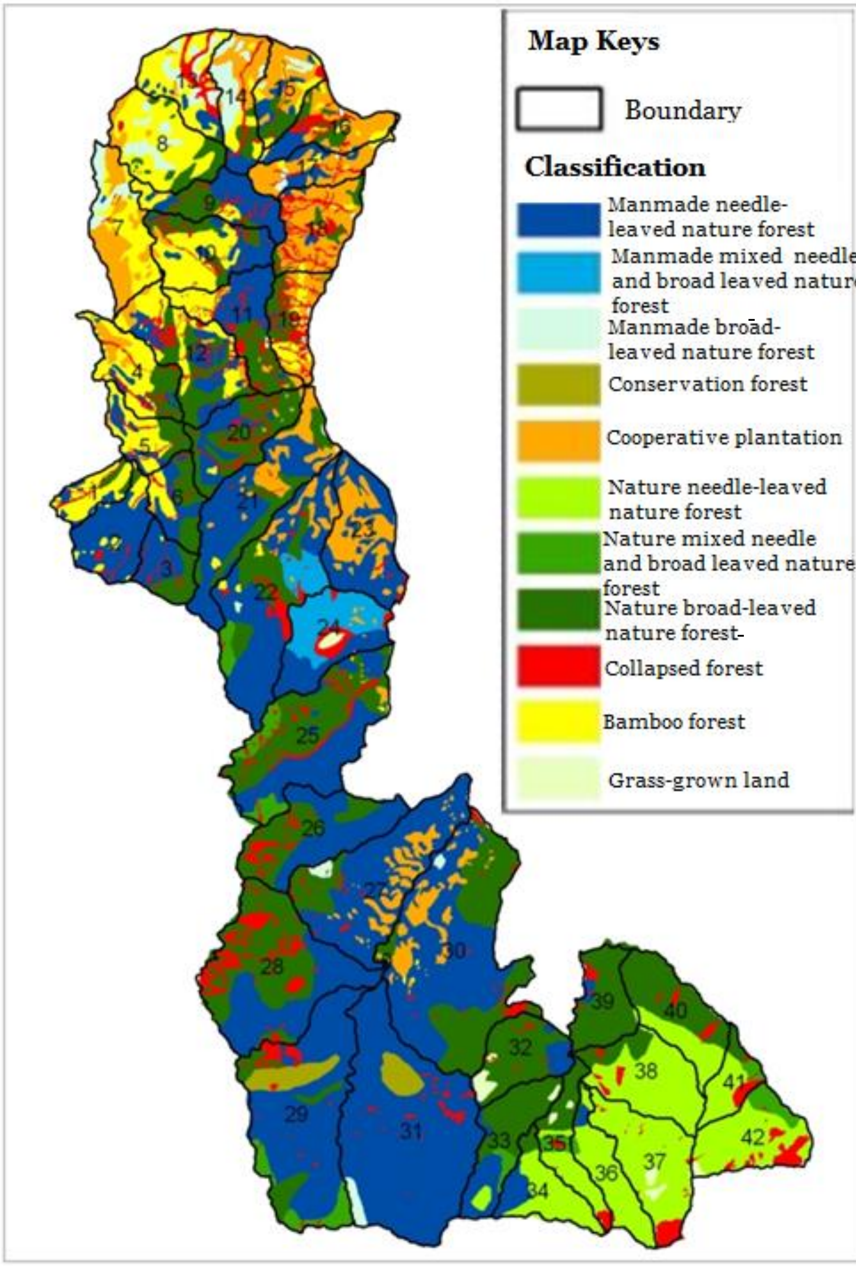

Fig. 2. Forest resource map of NTU experimental forest (Tsai 2018)

RESULTS AND DISCUSSION

Afforestation and Tending Operations, Recycled Resources, and Carbon Footprint Calculation

Table 2 shows the energy consumption, biomass, and emissions caused by the newly planted and tending operations in this study. The newly planted operations were higher than those of the tending operations in terms of energy consumption, biomass, and emissions because their processes are more complex. Because of the small size of the seedlings, special attention was required during weeding to avoid cutting them and producing more energy consumption and emissions. Furthermore, the high temperature and frequent rainfall at low altitude or the flatland afforestation sites in Taiwan resulted in the rapid growth of weeds that easily covered the seedlings. Therefore, the biomass of the weeds was relatively high during planting and afforestation operations. Ground objects, such as bamboo and miscellaneous wood, were also cut off during the soil preparation at the planting and afforestation stages, resulting in bamboo and miscellaneous wood biomass and higher energy consumption and emissions.

Because the renewable resources from the afforestation and tending operations were transported to the Wood Utilization and Practice Factory (Nantou, Taiwan), the pollution emissions from the abovementioned newly planted operations increased to 405.0 kg CO_2/ha, 50.1 g CH_4/ha, and 27.1 g N_2O/ha. The resulting emissions from the tending operations increased to 277.7 kg CO_2/ha, 36.3 g CH_4/ha, and 19.0 g N_2O/ha.

Table 2. Energy Consumption, Biomass, and Emissions from Newly Planted Forests and Tending Operations

Operation Forms	Newly Planted	Tending	P-value (t-test)
92 Unleaded Gasoline (L/ha)	41.2 ± 1.2	30.9 ± 1.1	1.84E-04
Weed Biomass (kg/ ha)	1237.2 ± 41.1	568.3 ± 51.5	4.32E-05
Bamboo Forest Biomass (kg/ha)	1120.0 ± 69.0	---	---
Miscellaneous Wood Biomass (kg/ha)	8239.0 ± 97.4	---	---
CO_2 (kg/ha)	92.3 ± 1.7	69.2 ± 4.0	2.18E-03
CH_4 (g/ha)	33.7 ± 2.3	25.3 ± 1.6	4.27E-03
N_2O (g/ha)	10.7 ± 0.6	8.0 ± 0.3	4.37E-03

The area of newly planted forests in the NTU experimental forest was 24,583 ha from 2008 to 2017, and the mid- and late-stage tending operations consisted of weeding (1,626 ha), vine removal (512 ha), pruning (132 ha), replanting (9 ha), thinning (144 ha), and cutting spreading bamboo (67 ha), equating to a total of 2,485 ha (Table 3). Table 3 shows the area of the newly planted forest and where weeding was completed during the mid- and late-stage tending operations, as well as the resulting emissions from 2008 to 2017. The newly planted forests produced average annual emissions of 995,693 kg CO_2, 123,171 g CH_4, and 66,625 g N_2O, whereas weeding during the mid- and late-stage tending operations caused average annual emissions of 69,147 kg CO_2, 9,039 g CH_4, and 4,731 g N_2O.

According to the reports published by the IPCC (IPCC 2006), basic density (BD) can be used to convert stem volume into stem biomass, which can then be converted into aboveground biomass using the biomass expansion factor (BEF) to estimate the carbon sequestration of forest trees. The forest timber volume produced from the thinning operations from 2008 to 2017 totaled 9,924 m^3. Assuming that the trees produced during the tending operations at this stage were *Cryptomeria japonica* (BD = 0.357 ton/m^3, BEF = 1.228), the carbon sequestration of the forest trees produced in the thinning operations at the NTU experimental forest was 637,517 kg/year. This was because of Article 8(2) of the Taiwan Forest Management Plan (Forestry Bureau, Council of Agriculture, Taiwan, 1997):

A comprehensive ban was applied to logging at natural forests, protection forest at reservoir catchment area, ecological protection zones, nature reserves, national parks, and afforestation areas that cannot be restored. Logging at experimental or test forests is prohibited unless for research or afforestation and tending needs.

Table 3. Afforestation and Mid- and Late-stage Tending Areas and Emissions at the National Taiwan University Experimental Forest 2008 to 2017

Year	Newly Planted				Tending			
	Area (ha)	CO_2 (kg)	CH_4 (g)	N_2O (g)	Area (ha)	CO_2 (kg)	CH_4 (g)	N_2O (g)
2008	685	277,425 ± 5,110	34,319 ± 2,342	18,564 ± 1,041	292	81,088 ± 1,493	10,600 ± 723	5,548 ± 311
2009	859	347,895 ± 6,408	43,036 ± 2,937	23,279 ± 1,305	304	84,421 ± 1,555	11,035 ± 753	5,776 ± 324
2010	2,493	1,009,665 ± 18,596	124,899 ± 8,524	67,560 ± 3,788	284	78,867 ± 1,453	10,309 ± 704	5,396 ± 303
2011	3,839	1,554,795 ± 28,637	192,334 ± 13,127	104,037 ± 5,834	297	82,477 ± 1,519	10,781 ± 736	5,643 ± 316
2012	3,683	1,491,615 ± 27,473	184,518 ± 12,593	99,809 ± 5,597	185	51,375 ± 946	6,716 ± 458	3,515 ± 197
2013	2,828	1,145,340 ± 21,095	141,683 ± 9,670	76,639 ± 4,298	245	68,037 ± 1,253	8,894 ± 607	4,655 ± 261
2014	3,545	1,435,725 ± 26,443	177,605 ± 12,121	96,070 ± 5,387	200	55,540 ± 1,023	7,260 ± 495	3,800 ± 213
2015	3,259	1,319,895 ± 24,310	163,276 ± 11,143	88,319 ± 4,952	253	70,258 ± 1,294	9,184 ± 627	4,807 ± 270
2016	1,707	691,335 ± 12,733	85,521 ± 58,37	46,260 ± 2,594	249	69,147 ± 1,274	9,039 ± 617	4,731 ± 265
2017	1,687	683,235 ± 12,584	84,519 ± 5,768	45,718 ± 2,564	181	50,264 ± 926	6,570 ± 448	3,439 ± 193
Avg.	2,459	995,693 ± 18,339	123,171 ± 8,406	66,625 ± 3,736	249	69,147 ± 1,274	9,039 ± 617	4,731 ± 265

Presently, the logging conducted at the NTU experimental forest is mainly thinning, improvement cutting after typhoon disasters, and logging of an experimental nature. Most of the main tree species retained at the forest land (*Cryptomeria japonica* and *Cunninghamia lanceolate*) have reached the rotation period (over 35 years) and have not been felled. Taiwan imports approximately 6 million m^3 of wood each year, with domestically produced wood accounting for merely 0.8% of the imported volume. Therefore, the timely rotation of trees that have surpassed their rotation period can contribute to the development and reuse rate of domestically produced wood in Taiwan in the future, and can form an industrial chain with local forestry to promote sustainable forestry development.

Refuse-derived Fuel from Renewable Forestry Materials

To understand the combustibility and pyrolysis behavior of renewable forestry resources, the characteristics of the renewable resources from the afforestation and tending operations at the artificial forest was conducted (Table 4). Because the miscellaneous trees contained bark, the moisture and ash contents were relatively high. The results revealed that the combustibility of the renewable resources from the afforestation and tending operations was 82.14% to 91.52%; thus, the miscellaneous trees can be considered as a favorable biomass fuel source. Table 4 shows the characteristics of the renewable materials from the afforestation and tending operations. The dry-basis calorific value of the miscellaneous wood was approximately 4,436 cal/g, which was approximately 80% of that of typical sub-bituminous coal and slightly lower than that of woody plants (approximately 4700 cal/g), but higher than that of herbaceous plants (approximately 4200 cal/g; Wahab *et al.* 2013). According to the American Society for Testing Materials (ASTM), the refuse-derived fuels can be divided into seven categories (RDF-*n*, with a higher *n* value indicating a higher fuel level; that is, higher energy efficiency). They include RDF-1: urban waste that is directly used as fuels; RDF-2: coarse-grained waste (95% of the waste can pass through a 6-in screen after being shattered); RDF-3: fine-grained waste (95% of the waste can pass through a 2-in screen after being shattered); RDF-4: pulverized combustibles (95% of them can pass through a 0.035-in screen); RDF-5: densified combustibles; RDF-6: combustibles that are processed into liquid fuels; and RDF-7: combustibles that are processed into gaseous fuels. Therefore, if the miscellaneous wood was properly mixed with other materials with a high calorific value and compressed into a block or rod (RDF-5), it can replace some coal and can be used in industrial applications, such as boiler combustion or power generation. The results of an elemental analysis (Elementar Vario EL Cube, CHN-OS Rapid, Langenselbold, Germany) showed that the contents of N and S were lower than the N or S content stipulated by the European Union's refuse-derived fuel regulations (N < 1.0%, S < 0.2%); thus, the refuse-derived fuel produced from the miscellaneous wood did not result in NO_x or SO_x pollution. Because the miscellaneous wood converted CO_2 into organic matter through photosynthesis, after the refuse-derived fuel was produced, the CO_2 originally fixed in the plants was emitted. Therefore, this biomass possesses a "carbon neutral" effect.

Table 4. Characteristics of the Recycled Resource from the Plantation Tending Processes

Sample	Proximate Analysis (%)			
	Moisture	Ash	Volatile Matter	Fixed Carbon
Renewable resources	10.50 ± 0.60	3.06 ± 0.11	81.10 ± 1.42	5.34 ± 0.14
Weed	6.34 ± 0.37	11.52 ± 0.71	67.84 ± 0.99	14.30 ± 1.2
Waste engine oil	6.40 ± 2.13	12.63 ± 5.25	80.85 ± 6.58	0.12 ± 0.02

	Calorific Value (cal/g)	Elemental Analysis (%)				
		C	H	O	N	S
Renewable resources	4436.5 ± 112.8	47.05 ± 0.48	6.41 ± 0.05	43.90 ± 1.31	0.08 ± 0.01	N.D.
Waste engine oil	10459.0 ± 60.9	82.83 ± 0.55	13.63 ± 1.21	1.37 ± 0.08	0.07 ± 0.01	N.D.

N.D.- not determined

Table 5 shows the characteristics of the refuse-derived fuel produced by adding miscellaneous wood to waste engine oil. According to Table 5, the addition of 20% of waste engine oil effectively increased the calorific value of the miscellaneous wood-derived fuel to 5,651 cal/g, which was in line with the procurement quality specifications for general sub-bituminous coal (calorific value > 5000 cal/g, moisture < 28%, ash < 8%, and sulfur < 1.1%) (Taiwan Power Company 2018). Moreover, different volumes of waste engine oil added had little effect on the combustion efficiency of the fuel produced from renewable resources. Therefore, using renewable resources to prepare refuse-derived fuel is less likely to produce air pollution, and it can be used as an alternative fuel for small boilers in the future.

Table 5. Characteristics of the Refuse-derived Fuel from Renewable Forestry Materials

Renewable Resources (%)	100	95	90	80
Waste Engine Oil (%)	0	5	10	20
Calorific Value (cal/g)	4,436.5 ± 112.8	4,753 ± 76.6	5,075 ± 93.2	5,651 ± 101.6
Ash (%)	3.06 ± 0.11	3.55 ± 0.29	3 .99 ± 0.31	4.87 ± 0.30
Nitrogen (%)	0.08 ± 0.01	0.08 ± 0.01	0.08 ± 0.01	0.08 ± 0.01
Sulfur (%)	N.D.	N.D.	N.D.	N.D.
Combustion Efficiency* (%)	97.2	97.5	97.8	98.1

* Combustion Efficiency (%) = $[CO_2]$ / ($[CO_2]$ + [CO]) × 100

CONCLUSIONS

1. This study examined the carbon emissions from afforestation and tending operations, and prepared refuse-derived fuels using the renewable resources from afforestation and tending operations. The results demonstrated that the afforestation and tending operations each produced 405.0 kg CO_2/ha and 277.7 kg CO_2/ha, which can be used as a reference for calculating the carbon footprint of forest management.
2. The renewable resources of the afforestation and tending operations were mainly miscellaneous wood and weeds, which were used to prepare a refuse-derived fuel to partly replace coal when they were pretreated, producing negligible NO_x or SO_x pollution.
3. The addition of 20% of waste engine oil effectively increased the calorific value of the fuel, which possessed characteristics that match the procurement specifications of general sub-bituminous coal as per the Taiwan Power Company. Therefore, the refuse-derived fuel could partly replace coal for fueling boiler combustion.

ACKNOWLEDGMENTS

The financial support from the Ministry of Science and Technology, Taiwan for the projects MOST 108-2621-M-002-026, MOST 107-2621-M-002-010 and MOST 107-2218-E-006-015 is gratefully acknowledged.

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Article submitted: March 27, 2019; Peer review completed: June 29, 2019; Revised version received: October 17, 2019; Accepted: November 1, 2019; Published: December 4, 2019.
DOI: 10.15376/biores.15.1.641-653