JOURNAL OF
ECOLOGY AND ENVIRONMENT
http://www.jecoenv.org

Research Paper
J. Ecol. Environ. 38(3): 281-291, 2015

A simple estimate of the carbon budget for burned and unburned *Pinus densiflora* forests at Samcheok-si, South Korea

Seok-Hwa Lim[1], Seung Jin Joo[2] and Keum-Chul Yang[3,*]

[1]Land & Housing Institute, Korea Land & Housing Corporation, Daejeon, 305-731, Korea
[2]Center for Atmospheric and Environmental Modeling, Seoul National University, Research Park, Seoul 151-919, Korea
[3]Department of Civil and Environmental Engineering, Kongju National University, Cheonan, 331-717, Korea

Abstract

To clarify the effects of forest fire on the carbon budget of a forest ecosystem, this study compared the seasonal variation of soil respiration, net primary production and net ecosystem production (NEP) over the year in unburned and burned *Pinus densiflora* forest areas. The annual net carbon storage (i.e., NPP) was 5.75 t C ha^{-1} in the unburned site and 2.14 t C ha^{-1} in the burned site in 2012. The temperature sensitivity of soil respiration (i.e., Q_{10} value) was higher in the unburned site than in the burned site. The annual soil respiration rate was estimated by the exponential regression equation with the soil temperatures continuously measured at the soil depth of 10 cm. The estimated annual soil respiration and heterotrophic respiration (HR) rates were 8.66 and 4.50 t C ha^{-1} yr^{-1} in the unburned site and 4.08 and 2.12 t C ha^{-1} yr^{-1} in the burned site, respectively. The estimated annual NEP in the unburned and burned forest areas was found to be 1.25 and 0.02 t C ha^{-1} yr^{-1}, respectively. Our results indicate that the differences of carbon budget and cycling between both study sites are considerably correlated with the losses of living plant biomass, insufficient nutrients and low organic materials in the forest soil due to severe damages caused by the forest fire. The burned *Pinus densiflora* forest area requires at least 50 years to attain the natural conditions of the forest ecosystem prior to the forest fire.

Key words: carbon budget, heterotrophic respiration, net primary production, soil temperature

INTRODUCTION

The carbon dioxide (CO_2) concentration has rapidly increased up to about 380 ppm at present by activities of human beings, compared to about 270 ppm before the industrial revolution (Aber and Melillo 2001). The impacts of the combustion of fossil fuel and intense land-uses have caused the fluctuation and imbalance of carbon cycle and budget in regional and global scales (Maier and Kress 2000). In particular, the forest ecosystem accounted for about 90% of carbon stock on the aboveground part within the terrestrial ecosystem, and 40% of carbon stock on the belowground part (Waring and Schlesinger 1985). Therefore, mitigation management has focused on the forest ecosystem as the pivotal sink in reducing the atmospheric CO_2 (Winjum et al. 1992).

About 10% of atmospheric CO_2 is generated from the soil, and their amounts are reached about 10 times more than the CO_2 emission according to consumption of the fossil fuel (Raich and Schlesinger 1992). As an index of metabolic activities through biological processes, the CO_2 efflux from the soil surface is generally termed soil

http://dx.doi.org/10.5141/ecoenv.2015.029

Received 1 November 2014, **Accepted** 3 April 2015

***Corresponding Author**
E-mail: yangkc@kongju.ac.kr
Tel: +82-41-521-9311

pISSN: 2287-8327 eISSN: 2288-1220

respiration, which plays major roles in the carbon cycle and budget of forest ecosystems (Anderson 1982, Landsberg and Gower 1997, Chae et al. 2003). Soil respiration mainly consists of two components: (a) heterotrophic respiration (HR) by soil microorganisms and soil animals that decompose litter and soil organic materials; and (b) root respiration (RR) from living plant roots and the associated mycorrhizae (Gough and Seiler 2004, Jassal and Black 2006). These biological processes are both largely affected by environmental factors, such as temperature, humidity, soil moisture content and soil physiochemical factors including litter supply, nutrients necessary for plant growth and soil bulk density in the forest ecosystems (Raich and Nadelhoffer 1989). However, because it is difficult to predict the spatio-temporal changes of soil respiration that results due to the complex variability of these factors, many studies should be established the correlation between the soil respiration and environmental factors (Mielnick and Dugas 2000, Xu and Qi 2001), and the carbon budget can be accurately expected through the quantitative measurement of soil respiration in various forest ecosystems (Wang et al. 2002).

In South Korea, forests occupy approximately 65% of the total terrestrial area (6.3×10^6 ha). The Korean forest is composed of both deciduous and mixed forests (about 57% of the Korean forest area) and *Pinus densiflora* forest (about 23.5% of the Korean forest area). Therefore, it is very important to quantify the carbon budget of Korean forests, and to determine whether the forest ecosystem is sink or source for atmospheric CO_2. Some previous studies of the carbon cycle and budget have been conducted in the Korean forests (Pyo et al. 2003, Joo et al. 2011). However, there is still a lack of information. The forest area in the Gangwon-do district of South Korea has been concentrated more than 21% of the total Korean forest area. In recent years, forest fire has frequently occurred in this district, and the damaged areas have increased from year to year. The largest damage accounted for about 0.36% (23,794 ha) out of the total Korean forest area in 2000 (Choung et al. 2004). Forest fire causes a rapid reduction of biomass and a change of community structure by burning inflammable substances within the forest (Díaz-Delgado et al. 2002). Moreover, repetitive forest fires, further drive subsequent changes in the species composition of soil organisms, physicochemical properties of the soil and forest vegetation in ways that probably alter the carbon balance and nutrient cycle of the entire ecosystem (Chandler et al. 1983, Mun and Choung 1996). Although ecological long-term studies are necessary to assess the carbon budget of forest ecosystems according to the intensity of forest fire and the degree of the ecosystem recovery, there is no comprehensive study for the effects of forest fire on the carbon budget in the Korean forests.

We have attempted to investigate the seasonal variation of soil respiration, net primary production (NPP) and net ecosystem production (NEP) over the year in both the unburned and the burned *P. densiflora* forest in the forest area damaged by the eastern coast forest fire of 2000, which has gone through the natural recovery period for 12 years around Samcheok-si, Gangwon-do, South Korea. The main part of the burned *P. densiflora* forest has been preserved for national long-term ecological research by the Ministry of Environment. There have been no artificial forest management practices and treatments. The present study is aimed specifically at clarifying the effects of forest fire on the carbon budget of the forest ecosystem by comparing the soil respiration rate, NPP and NEP in the unburned and burned forest areas.

MATERIALS AND METHODS

Study site

The subject area for this study is located in Samcheok-si, Gangwon-do, dominated by pine tree (*Pinus densiflora*). The burned forest site which is located on Imwon-ri, Wondeok-up (N 37° 13′ 47.8″, E 129° 18′ 36.3″) has been in the recovery for 12 years after being damaged by the forest fire, which consumed nearly 70% of the total forested area regionally (Fig. 1). The vegetation of this site was completely burnt during the fire up to the crown layer of dominant pine trees due to the forest fire. Subsequent to the fire, oak trees (*Quercus mongolica*) dominated throughout the shrub layer, with the additional presence of *Quercus serrata* and *Lespedeza bicolor*. The unburned forest site is located on Yang-ri, Geundeok-myeon (N 37° 19′ 42.0″, E 129° 12′ 10.6″) and is dominated by 45 year-old pine trees with the density of about 1000 trees ha^{-1}. In the tree layer of unburned forest site, the diameter at breast height is 26.64 ± 7.30 cm and the height is 15.87 ± 0.51 m (mean ± standard deviation) with abundant *Q. serrata* and *Q. mongolica* and occasional *Q. variabilis*, *Castanea crenata*, and *Rhododendron mucronulatum var. ciliatum*.

In July 2007, we established 4 permanent study plots (20 m × 20 m per one permanent study plot) on a gentle slope (about 10°~20°) in each burned and unburned site. Being as located in the eastern coast of Korea, the study area shows the higher mean annual temperature of 13.2℃ characteristic of the oceanic climate. The annual

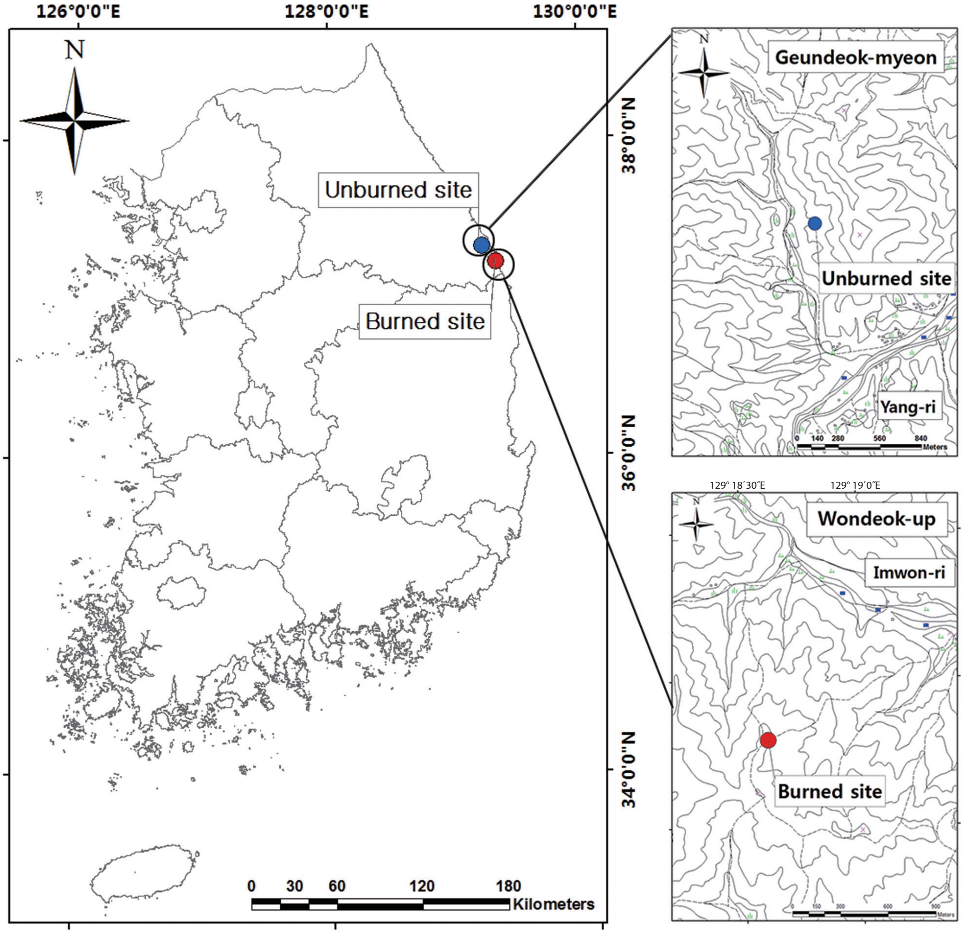

Fig. 1. Map of the study area in Samcheck-si, Gangwon-do (blue dot indicates the unburned study site at Geundeok-myeon Yang-ri; red dot indicates the burned study site at Wondeok-up Imwon-ri).

total precipitation and annual mean wind velocity were 1273.9 mm and 2.2 m/s, respectively. The precipitation is concentrated during the peak summer season (July and August), accounting for more than 50% of the annual total precipitation.

Biomass and net primary production

In 4 permanent study plots (the total area of 1600 m^2) per each site, the biomasses of all vegetation were measured once a year during the experimental period from 2007 to 2012. In all standing trees of 4 permanent study plots, the diameter at breast height (DBH, at the 1.2 m height above the ground) and the height (H) were measured with measuring tapes and ultrasonic distance meters (Hagalöf Vertex Laser VL400; Sweden), respectively (Hoover 2008, Son et al. 2010). The basal diameter of trees more than 1 cm diameter at 10 cm height above the ground was measured. The standing biomass of tall trees was estimated using the biomass allometric equation by the DBH and H of pine trees in Gangwon-do (Son et al. 2010). The above-ground biomass of shrubs was estimated using the allometric equation established by Lee et al. (2004). In addition, the total below-ground biomass was estimated to be 25% of the total above-ground biomass (Johnson and Risser 1974). The harvest method was used for measuring the current total biomass of herb layers. The above- and below-ground parts of herbs were collected by clipping and/or digging from 3 random quadrats (2 m × 2 m) adjacent to the permanent study plot. The current biomass per unit area was calculated by weighing after drying until the constant weight at 60 °C. The annual total amount of net primary production (NPP) was estimated by subtracting biomass of the previous year from biomass of the current year.

Measurement of soil respiration

In October 2011, we randomly selected locations of 2 sub-plots (120 cm × 80 cm) in each permanent study plot. Three soil collars (6 collars per each permanent study plot) made of cylindrical polyvinyl (10 cm in diameter and 7 cm in height) were inserted into the soil in each subplot to a depth of 2 cm. The above-ground vegetation was removed from inside the collars, but the surface litter was retained. Once inserted, the soil collars were left in place throughout the entire measurement period in each subplot. The form gasket ring was used to form an airtight seal between the soil collar and the soil respiration chamber. In situ soil respiration rates were measured once a month from November 2011 to October 2012 with by connecting to an infrared gas analyzer LI-6400 (Li-Cor Inc., Lincoln, NE, USA) based on the closed chamber method (Chae et al. 2003, Joo et al. 2011). The measurements were regularly performed between 10:00 and 14:00 h to avoid diurnal fluctuations as much as possible (Davidson et al. 1998). We calculated the daily mean values by assuming that the measured soil respiration rates were repeated over the day, and each sampling date was considered as the reasonable midpoint of a sampling period. To estimate annual soil respiration, we interpolated between sampling dates to estimate the mean soil respiration for each site each day of the year, and then computed the sum for the year (Davidson et al. 1998).

Measurements of environmental factors

The soil temperature and soil moisture content at the soil depth of 10 cm and the air temperature at 1.5 m height above the ground were automatically measured at 10 min interval for one year from November 2011 to October 2012 by installing each Data loggers (WatchDog 1000 Series; Spectrum Technologies Inc.) in the unburned and burned forest sites.

Estimation of carbon budget

In *Pinus densiflora* forests of Asian monsoon temperate regions, the ratio of root respiration (RR) to the soil respiration has been reported in the range of 45 - 51% (Nakane et al. 1983), and in the present study we used the mean value of 48%. We used the estimate of 50% for the carbon content in the xylem of the trees and shrubs that has been internationally used (IPCC 2007), with 45% as the estimate of the amount of carbon for the herbs (Houghton et al. 1983). The net ecosystem production (NEP) can be generally calculated by subtracting heterotrophic respiration (HR) from net primary production (NPP) by vegetation (NEP = NPP – HR) (Lee et al. 2003, Yashiro et al. 2010). The NPP can be also calculated by deducting autotrophic respiration (AR) from gross primary production (GPP) by vegetation (NPP = GPP – AR). NPP in the forest ecosystems indicates the total amount of carbon in the biomass in the in the current year, minus the previous year. Heterotrophic respiration (HR) was calculated by subtracting root respiration (RR) from the soil respiration (HR = soil respiration – RR).

Statistical analysis

Differences between the mean values of the soil respiration rates for unburned and burned study sites were evaluated using the Student's *t*-test. Significant levels for all tests were $P < 0.05$. Regression analysis was used to analyze the relationships among soil respiration rates, soil and air temperatures, and soil moisture contents in unburned and burned study sites. We explained the sensitivity of the mean soil respiration rate to soil and air temperatures by fitting exponential functions to the data. We also examined the sensitivity of the mean soil respiration rate to soil moisture content by fitting second-order polynomial functions to the data. All statistical analyses were conducted using the statistical analysis program of SPSS ver. 12.0 (SPSS Inc., Chicago, IL, USA).

RESULTS AND DISCUSSION

Standing biomass and NPP

In both the unburned and burned study sites, the pine tree was the only dominate species (Table 1). The relatively low density of dominant pine trees in the unburned site had developed an overall structure of diverse layers within the forest. In the case of burned site, shrubs had mainly developed the architecture and distribution of understory vegetation. We assumed that the high density of shrubs of uniform height in the burned site was due to growth subsequent to the 2000 fire.

The standing biomasses of the separate tree, shrub, and herb layers in the unburned and burned sites are shown in Table 2. The total standing biomass of the unburned site in 2011 and 2012 was 327.18 t/ha and 338.68 t/ha (1 t = 10^3 kg), respectively. In the same period, the total standing biomass of the burned site was 74.57 t/ha and 78.84 t/ha, respectively. In our study, the amount of standing biomass in the unburned *P. densiflora* forest was higher than 92.35 t/ha in Mt. Nam (Lee 2011), 119.84 t/ha in Mt. Worak (Jeon 2007), and about 206 t/ha in Mt. Jeombong (Kwak 2008). Among them, the differences in the standing biomass of *P. densiflora* forests of South Korea can be varied by the age of trees, districts, environmental conditions, and the applied allometric equations (Park et al. 1996).

The net primary production (NPP) in the unburned and burned study sites in 2012 is shown in Table 3. NPP in the unburned site was 11.50 t ha^{-1} yr^{-1} while NPP in the

Table 1. Dominant vegetation in the unburned and burned study sites in 2012

Study plot		Species composition	Density (No. of tree/100 m^2)	Height (m)	DBH (cm)
Unburned site	Tree	*Pinus densiflora*	10	15.87 ± 0.51	26.64 ± 7.30
	Shrub	*Quercus serrata* *Quercus mongolica* *Quercus dentata* *Castanea crenata* *Rhododendron mucronulatum*	39	2.02 ± 0.78	2.65 ± 1.21
	Herb	*Carex lanceolata*	-	-	-
Burned site	Shrub	*Quercus mongolica* *Quercus serrata* *Lespedeza bicolor*	60	2.44 ± 0.97	3.74 ± 2.15
	Herb	*Carex lanceolata*	-	-	-

DBH, the diameter at breast height.

Table 2. Above- and below-ground biomasses in the unburned and burned study sites in 2011 and 2012

Vegetation		Unburned site		Burned site	
		2011	2012	2011	2012
Tree	Stem	170.65	176.44		
	Branch	48.54	49.95		
	Leaf	21.42	21.94		
	Root	57.95	59.74		
	Total	298.56	308.07		
Shrub	Aboveground	22.58	24.16	59.20	62.61
	Belowground	5.65	6.04	14.80	15.65
	Total	28.23	30.20	74.00	78.26
Herb	Aboveground	0.22	0.24	0.33	0.33
	Belowground	0.17	0.17	0.24	0.25
	Total	0.39	0.41	0.57	0.58
Total (t/ha)		327.18	338.68	74.57	78.84

Table 3. The net primary production (NPP) and annual net carbon storage in the burned and unburned study sites in 2012

NPP		Unburned site	Burned site
		2012	2012
Tree	Stem	5.78	
	Branch	1.41	
	Leaf	0.52	
	Root	1.79	
	Total	9.50	
Shrub	Aboveground	1.58	3.41
	Belowground	0.40	0.85
	Total	1.98	4.26
Herb	Aboveground	0.021	0.008
	Belowground	-0.001	0.002
	Total	0.02	0.01
Total (t ha^{-1}yr^{-1})		11.50	4.27
Annual net carbon storage (t C ha^{-1}yr^{-1})		5.75	2.14

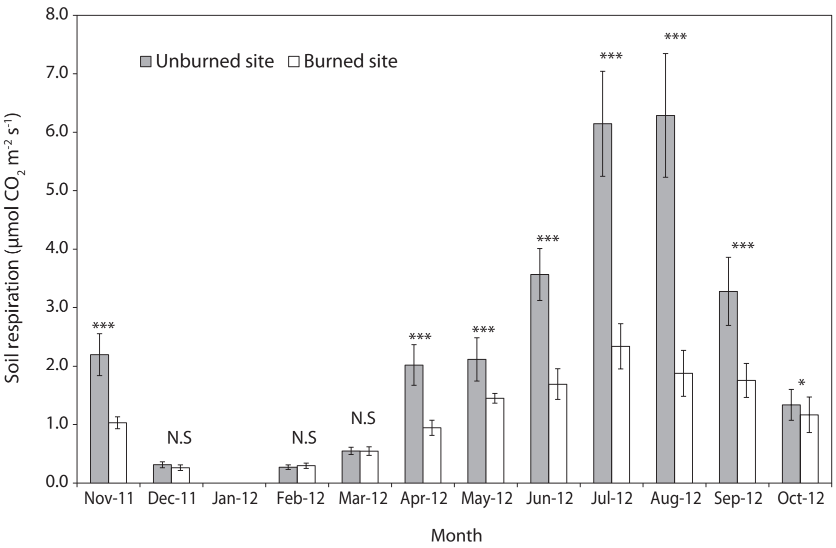

Fig. 2. Seasonal patterns of soil respiration rates in the unburned and burned study sites (Student's *t*-test: *, $P < 0.05$; ***, $P < 0.001$; N.S, no significance). Vertical bars indicate standard deviations of the mean. Very little soil respiration occurs during the winter (December through March).

burned site was 4.27 t ha^{-1} yr^{-1}. The NPP in the unburned *P. densiflora* forest was higher than 6.13 t ha^{-1} yr^{-1} in Mt. Nam (Lee 2011), whereas it was lower than 12.24 t ha^{-1} yr^{-1} in Mt. Jeombong (Kwak 2008). In our study, although the NPP in the burned site was lower than those in other studies, it was included within the range of 3.7–16.5 t ha^{-1} yr^{-1} for the annual net production of *P. densiflora* forests in South Korea reported by Park and Lee (1990). The annual net carbon storage of vegetation (i.e., NPP) was 5.75 t C ha^{-1} in the unburned study site and 2.14 t C ha^{-1} in the burned study site during the study period of 2012 (Table 3).

Characteristics of soil respiration

Seasonal variations of soil respiration rates in the unburned and burned study sites are shown in Fig. 2. During the entire experiment period from November 2011 to October 2012, the monthly mean soil respiration rate was 2.74 ± 0.49 μmol CO_2 m^{-2} s^{-1} in the unburned site and 1.37 ± 0.26 μmol CO_2 m^{-2} s^{-1} in the burned site. In the peak summer season (July and August), the soil respiration rates in the unburned study site was more than three times than that of a maximum value in the burned study site. However, in in the winter season (December–February) and early spring (March) with the relatively low rates of soil respiration for one year, there were no significant differences between the unburned and burned study sites (Fig. 2). The plant root growth and the metabolic activities of heterotrophic soil microorganisms were most similar between the 2 plant communities during the winter period. Although the activity of heterotrophic soil microorganisms in the burned study site were at a maximum during the summer season, their soil respiration rates were always lower than those in the unburned study site.

Correlation between the soil respiration rates and environmental factors

Relationships between the environmental factors (air and soil temperatures, and soil moisture content) and the soil respiration rates was analyzed by fitting exponential and second-order polynomial functions to the data are shown in Fig. 3. The soil respiration rates in the unburned ($R^2 = 0.97$) and burned ($R^2 = 0.94$) sites had a strong correlation with soil temperatures. They were more sensitive to the soil temperature than the air temperature in both sites. Moreover, the Q_{10} values (the temperature sensitivity of soil respiration) in the unburned site were higher than those in the burned site. In addition, the relationship between the soil moisture content and soil respiration presented a very low correlation in the unburned ($R^2 = 0.28$) and burned ($R^2 = 0.14$) sites (Fig. 3). These finding results were similar to those reported in many forest ecosystems (Witkamp 1969, Chapman 1979, Son and Kim 1996, Knapp et al. 1998, McHale et al. 1998, Lee and Mun 2001, Yi 2003). However, Davidson et al. (1998) found that soil respiration may be decreased in some periods with high or low soil moisture content. Knapp et al. (1998) reported that the soil respiration rate was increased with the improved metabolic activity of heterotrophic microor-

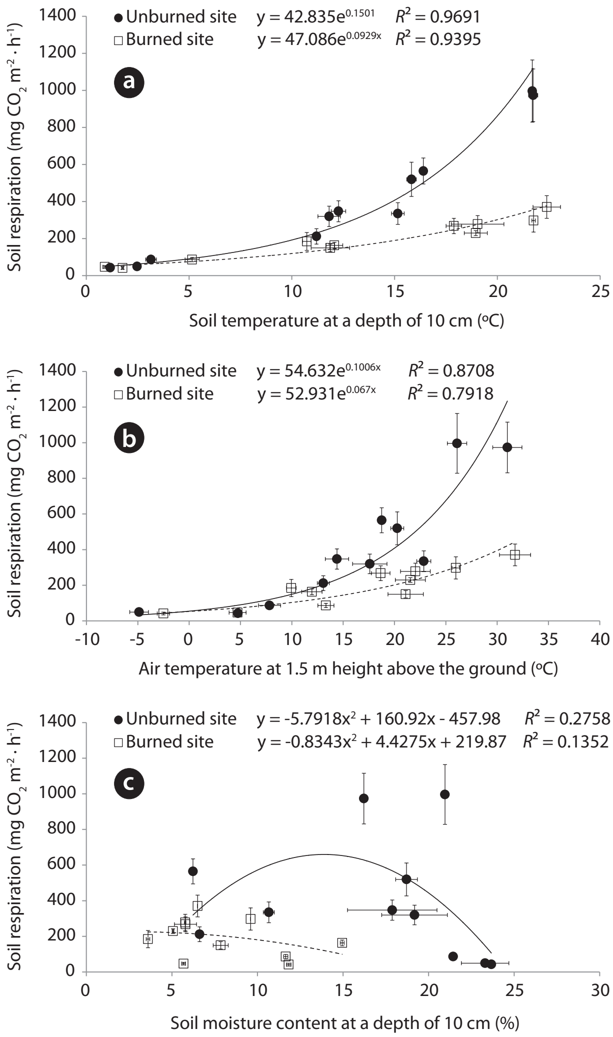

Fig. 3. Relationships between the soil respiration rate and soil temperature (a), air temperature (b) and soil moisture content (c) in the unburned and burned study sites. The solid and dashed lines represent regression curves for the unburned site and burned site, respectively.

ganisms by rising soil moisture contents. Lee (2011) also showed that that the soil respiration rate was heightened with the increase of soil microbial activity by the activated diffusion of oxygen into the soil pore for a certain period after rainfall. Although in our study, the relationship between the soil respiration rate and soil moisture content was a very low, the soil moisture content was recognized as an important secondary environmental factor (Reiners 1968, Crapo and Coleman 1972). Therefore, further detailed studies are needed to examine and clarify the influences of environmental (soil moisture content, solar radiation, precipitation and temperature) and biotic (soil microbial and faunal activity, litter production, and plant root growth) factors on the soil respiration rate in various forest ecosystems.

Total annual soil respiration

The annual soil respiration in the unburned and burned study sites was 31.76 and 14.95 t CO_2 ha^{-1} yr^{-1}, respectively (Table 4). The annual soil respiration rate in the unburned study site was two times higher than that in the burned site. In our study, the annual soil respiration in the unburned *P. densiflora* forest was higher than 24.0 t CO_2 ha^{-1} yr^{-1} in Jinju districts of Kyeongnam (Moon 2004), 27.32 t CO_2 ha^{-1} yr^{-1} in Mt. Sambong of Kyeongnam (Kim 2006), 21.20 t CO_2 ha^{-1} yr^{-1} in Chuncheon districts of Gangwon-do (Jeong 2007), and 26.27 t CO_2 ha^{-1} yr^{-1} in Mt. Moodeung (Kim 2008). The annual soil respiration in the burned *P. densiflora* forest was lower than those in above other studies. However, it was a little higher than the annual value of 10.0 t CO_2 ha^{-1} yr^{-1} in the burned *P. densiflora* forest for 1 year after the forest fire reported by Jeong (2007). In addition, the values of annual soil respiration in both unburned and burned forests were incorporated within the range of 10.0–46.0 t ha^{-1} yr^{-1} for various coniferous forests in studies of soil CO_2 effluxes from the soil surface reviewed by Raich and Nadelhoffer (1989).

Table 4. Seasonal and annual soil respiration rates in the unburned and burned study sites

2012	Unburned site		Burned site	
Month	Soil respiration	Percentage (%)	Soil respiration	Percentage (%)
Spring (March ~ May)	464.88	14.64	300.13	20.08
Summer (June ~ August)	1752.97	55.20	636.17	42.56
Autumn (September ~ November)	810.41	25.52	428.96	28.69
Winter (December ~ February)	147.27	4.64	129.49	8.67
Monthly total (g CO_2 m^{-2})	3175.53	100	1494.77	100
Annual (t CO_2 ha^{-1})	31.76		14.95	
Annual (t C ha^{-1})	8.66		4.08	

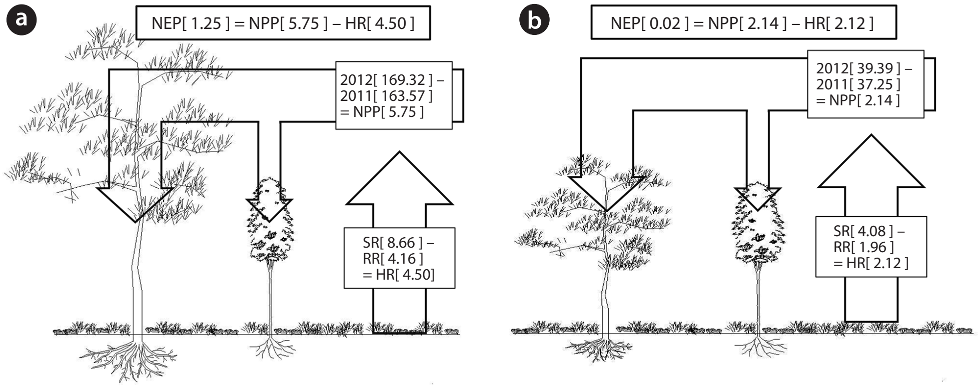

Fig. 4. Carbon budgets in the unburned (a) and burned forest areas (b) in 2012 (t C ha^{-1}, 1 t = 10^3 kg). NEP, net ecosystem production; NPP, net primary production; HR, heterotrophic respiration; SR, soil respiration; RR, root respiration.

Carbon budget

The annual NPP in the unburned and burned *P. densiflora* forests was 5.75 and 2.14 t C ha^{-1} yr^{-1} respectively, while the annual heterotrophic respiration (HR) was 4.50 and 2.12 t C ha^{-1} yr^{-1} respectively (Fig. 4). With this, the annual NEP in the unburned and burned forest areas was calculated as 1.25 and 0.02 t C ha^{-1} yr^{-1} respectively. These results suggest that both unburned and burned *P. densiflora* forests reflect the function of forest ecosystem as sinks of atmospheric CO_2 in 2012. However, the burned forest areas might have acted as a source until the recent few years.

Recovery period for the forest fire

In the unburned and the burned study sites, the annual total standing biomass of vegetation except for the herb layer during the survey period of six years from 2007 to 2012 is shown in Table 5. Annual mean growth rates were documented as 8.83 t ha^{-1} yr^{-1} in the unburned site and 4.08 t ha^{-1} yr^{-1} in the burned site (Fig. 4). The estimated annual total standing biomass in the burned site prior to the forest fire by applying the annual mean growth rate in the unburned site was about 232.3 t ha^{-1} yr^{-1}. It was assumed to need about 38 years until the burned study site become to the standing biomass in the *P. densiflora* forest prior to the fire, through the natural recovery period of 12 years after the forest fire. Therefore, since the eastern coast forest fire of South Korea in 2000, the damaged *P. densiflora* forest areas are required at least 50 years to become the optimum conditions of the forest ecosystem prior to the fire. In the present of 2012, the burned *P. densiflora* forest areas have recovered by about 24%.

CONCLUSION

This study was conducted in the unburned *P. densiflora* forest, and the burned *P. densiflora* forest in which the area damaged by the eastern coast forest fire in 2000 , which has gone through the natural restoration process and the recovery period for 12 years around Samcheok-si, Gangwon-do, South Korea. The annual net carbon stor-

Table 5. Annual total standing biomasses (t/ha) in the unburned and burned study sites during the survey period of 6 years from 2007 to 2012

Year	Unburned site	Burned site
2007	294.13	57.89
2008	301.07	60.13
2009	309.97	64.24
2010	316.52	68.82
2011	326.79	74.00
2012	338.27	78.27
Annual mean growth rate (t ha^{-1} yr^{-1})	8.83	4.08

age of vegetation (i.e., NPP) in 2012 was 5.75 t C ha^{-1} in the unburned forest and 2.14 t C ha^{-1} in the burned forest. During the entire experiment period, the monthly mean soil respiration rate was 2.74 ± 0.49 μmol CO_2 m^{-2} s^{-1} in the unburned site and 1.37 ± 0.26 μmol CO_2 m^{-2} s^{-1} in the burned site. The soil respiration rate in both sites had a strong correlation with the soil temperature. The temperature sensitivity of soil respiration (i.e., Q_{10} value) was higher in the unburned site than those in the burned site. The estimated annual total soil respiration and heterotrophic respiration (HR) were 8.66 and 4.50 t C ha^{-1} yr^{-1} in the unburned site and 4.08 and 2.12 t C ha^{-1} yr^{-1} in the burned site, respectively. The estimated annual NEP in the unburned and burned forests was found to be 1.25 and 0.02 t C ha^{-1} yr^{-1}, respectively. Our results indicate that the differences of carbon cycle and budget between the unburned and burned sites are considerably attributed to the losses of living plant biomass in the above and belowground of *P. densiflora* forest due to the huge damage caused by the forest fire, and insufficient nutrients and low organic materials in the forest soil of burned site. Although both unburned and burned forests play as sinks of atmospheric CO_2, the burned forest areas might have acted as a source until the recent few years. It was found that the damaged *P. densiflora* forest area is required at least 50 years to become the natural conditions of the forest ecosystem prior to the forest fire. It seems that the burned *P. densiflora* forest areas have recovered by about 24% in the present of 2012. However, in fact, it is difficult to reveal the impacts of forest fire in related to the carbon cycle and budget of *P. densiflora* forest ecosystem, only with the results obtained by field measurements during this short-term research period. Therefore, further detailed and long-term studies are necessary to establish an accurate evaluation of the carbon balance and dynamics in the burned *P. densiflora* forest until the damaged forest ecosystem completely becomes a natural recovery into the initial state prior to the forest fire.

ACKNOWLEDGMENTS

This work was funded by the Korea Meteorological Administration Research and Development Program (Grant No. KMIPA 2015-6040). We thank all researchers under the environmental and ecological laboratory of Kongju National University for their field assistance.

LITERATURE CITED

Aber JD, Melillo JM. 2001. Terrestrial ecosystems, 2nd Ed. Academic Press, San Diego, CA.

Anderson JPE. 1982. Soil respiration. In: Methods of soil analysis, Part 2: Chemical and microbiological properties (Page AL, Miller RH, Keeney DR, eds). American Society of Agronomy, Madison, WI, pp 831-871.

Chae NY, Kim J, Kim DG, Lee DW, Kim RH, Ban JY, Son YH. 2003. Measurement of soil CO_2 efflux using a closed dynamic chamber system. Korean J of Agric For Meteorol 5: 94-100.

Chandler C, Cheney P, Thomas P, Trabaud L, Williams D. 1983. Fire in forestry, Vol. I: Forest fire behavior and effects. Wiley, New York, NY.

Chapman SB. 1979. Some interrelationships between soil and root respiration in lowland *Calluna* heathland in southern England. Ecology 67: 1-20.

Choung Y, Lee BC, Cho JH, Lee KS, Jang IS, Kim SH, Hong SK, Jung HC, Choung HL. 2004. Forest responses to the large-scale east coast fires in Korea. Ecol Res 19: 43-54.

Crapo NL, Coleman DC. 1972. Root distribution and respiration in a Carolina old field. Oikos 23: 137-139.

Davidson EC, Belk E, Boone RD. 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Glob Chang Biol 4: 217-227.

Díaz-Delgado R, Lloret F, Pons X, Terradas F. 2002. Satellite evidence of decreasing resilience in Mediterranean plant communities after recurrent wildfires. Ecology 83: 2293-2303.

Gough CM, Seiler JR. 2004. The influence of environmental, soil carbon, root, and stand characteristics on soil CO_2 efflux in loblolly pine (*Pinus taeda L.*) plantations located on the South Carolina Coastal Plain. For Ecol Manag 191: 353-363.

Hoover CM. 2008. Field measurements for forest carbon monitoring: a landscape-scale approach. Springer Science & Business Media, New York, NY.

Houghton RA, Hobbie JE, Melillo JM, Moore B, Peterson BJ, Shaver GR, Woodwell GM. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere. Ecol Monogr 53: 235-262.

Intergovernmental Panel on Climate Change (IPCC). 2007. The 5th Assessment Report. The physical science basis. Cambridge University Press, Cambridge.

Jassal RS, Black TA. 2006. Estimating heterotrophic and autotrophic soil respiration using small-area trenched plot technique: Theory and practice. Agric For Meteorol 140:

193-202.

Jeon IY. 2007. Organic carbon and nutrient distribution in *Pinus densiflora* forest at Mt.Worak national park. MS thesis. Kongju National University, Gongju, Korea. (in Korean with English abstract)

Jeong MJ. 2007. Soil respiration and soil microbial activity after fire in a *Pinus densiflora* stand. MS thesis. Kangwon National University, Chuncheon, Korea. (in Korean with English abstract)

Johnson FL, Risser PG. 1974. Biomass, annual net primary production and dynamics of six mineral elements in a post oak-blackjack oak forest. Ecology 55: 1246-1258.

Joo SJ, Park MS, Kim GS, Lee CS. 2011. CO_2 flux in a cool-temperate deciduous forest (*Quercus mongolica*) of Mt. Nam in Seoul, Korea. J Ecol Field Biol 34: 95-106.

Kim C. 2006. Soil carbon cycling and soil CO_2 efflux in a Red Pine (*Pinus densiflora*) stand. J Ecol Field Biol 29: 23-27.

Kim SB. 2008. Soil CO_2 efflux and leaf-litter decomposition in *Pinus densiflora* and *Quercus variabilis* stands. MS thesis. Chonnam National University, Gwangju, Korea. (in Korean with English abstract)

Knapp AK, Conard SL, Blair JL. 1998. Determinants of soil CO2 flux from a sub–humid grassland: Effect of fire and fire history. Ecol Appl 8: 760-770.

Kwak TB. 2008. Comparative study for the phytomass, NPP and organic carbon budget among *Quercus mongolica*, *Quercus mongolica-Abies holophylla* and *Pinus densiflora* communities in Mt. Jumbong, Korea. MS thesis. Gangneung National University, Gangneung, Korea. (in Korean with English abstract)

Landsberg JJ, Gower ST. 1997. Application of physiological ecology to forest management. Academic Press, San Diego, CA.

Lee JS. 2011. Monitoring soil respiration using an automatic operating chamber in a Gwangneung temperate deciduous forest. J Ecol Field Biol 34: 411-423.

Lee KS, Choung YS, Kim SC, Shin SS, Noh CH, Park SD. 2004. Development of vegetation structure after forest fire in the east coastal region, Korea. Korean J Ecol 27: 99-106.

Lee MS, Nakane K, Nakatsubo T, Koizumi H. 2003. Seasonal changes in the contribution of root respiration to total soil respiration in a cool-temperate deciduous forest. Plant Soil 255: 311-318.

Lee SK. 2011. Production and litter decomposition and organic carbon distribution in *Pinus densiflora* and *Quercus mongolica* and *Robinia pseudoacacia* forests at Mt. Nam. MS thesis. Kongju National University, Gongju, Korea. (in Korean with English abstract)

Lee YY, Mun HT. 2001. A study on the soil respiration in a *Quercus acutissima* forest. Korean J Ecol 24: 141-147. (in Korean with English abstract)

Maier CA, Kress LW. 2000. Soil CO_2 evolution and root respiration in 11 year-old lobolly pine (*Pinus taeda*) plantations as affected by moisture and nutrient availability. Can J For Res 30: 347-359.

McHale PJ, Mitchell MJ, Bowles FP. 1998. Soil warming in a northern hardwood forest: Trace gas fluxes and leaf litter decomposition. Can J For Res 28: 1365-1372.

Mielnick PC, Dugas WA. 2000. Soil CO_2 flux in a tall grass prairie. Soil Biol Biochem 32: 221-228.

Moon HS. 2004. Soil respiration on *Pinus densiflora*, *Quercus variabilis* and *Platycarya strobilacea* stands in Jinju, Gyeongnam province. Korean J Ecol 27: 87-92. (in Korean with English abstract)

Mun HT, Choung YS. 1996. Effects of forest fire on soil nutrients in pine forests in Kosong, Kangwon province. Korean J Ecol 19: 375-383. (in Korean with English abstract)

Nakane K, Yamamoto M, Tsubota H. 1983. Estimation of root respiration rate in a mature forest ecosystem. Jpn J Ecol 33: 397-408.

Park IH, Lee DK, Lee KJ, Moon GS. 1996. Growth, biomass and net production of *Quercus* species. J Korean For Soc 85: 76-83.

Park IH, Lee SM. 1990. Biomass and net production of *Pinus densiflora* natural forests of four local forms in Korea. J Korean For Soc 79: 196-204.

Pyo JH, Kim SW, Mun HT. 2003. A study on the carbon budget in *Pinus koreansis* plantation. Korean J Ecol 26: 129-134.

Raich JW, Nadelhoffer KJ. 1989. Belowground carbon allocation in forest ecosystems: Global trends. Ecology 70: 1346-1354.

Raich JW, Schlesinger WH. 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus 44B: 81-99.

Reiners WA. 1968. Carbon dioxide evolution from the floor of three Minnesota forests. Ecology 49: 471-483.

Son YM, Lee KH, Kim RH, Pyo JK, Park IH, Son YW, Lee YJ, Kim CS. 2010. Carbon emission factors of major species for the inventory of greenhouse gas in Korean forests. Korea Forest Research Institute. (in Korean)

Son YW, Kim HW. 1996. Soil respiration in *Pinus rigida* and *Larix leptolepis* plantations. J Korean For Soc 85: 496-505. (in Korean with English abstract)

Wang G, Qian J, Cheng G, Lai Y. 2002. Soil organic carbon pool of grassland soils on the Qinghai-Tibetan Plateau and its global implication. Sci Total Environ 291: 207-217.

Waring RH, Schlesinger WH. 1985. Forest ecosystem; Concept and management. Academic Press, New York, NY.

Winjum JK, Dixon RK, Schroeder PE. 1992. Estimating the global potential of forest and agro-forest management practices to sequester carbon. Water Air Soil Pollut 64: 213-227.

Witkamp M. 1969. Cycle of temperature and carbon dioxide evolution from the forest floor. Ecology 47: 492-494.

Xu M, Qi Y. 2001. Soil-surface CO_2 efflux and its spatial and temporal variations in a young ponderosa pine plantation in northern California. Glob Chang Biol 7: 667-677.

Yashiro Y, Lee NYM, Ohtsuka T, Shizu Y, Saitoh TM, Koizumi H. 2010. Biometric-based estimation of net ecosystem production in a mature Japanese cedar (*Cryptomeria japonica*) plantation beneath a flux tower. J Plant Res 123: 463-472.

Yi MJ. 2003. Soil CO_2 evolution in *Quercus variabilis* and *Q. mongolica* forests in Chunchon, Kangwon province. J Korean For Soc 92: 263-269.