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Organic carbon distribution and budget of dominant woody plant community in the subalpine zone at volcanic Jeju Island, Korea

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Abstract

Background: The Northern Hemisphere forest ecosystem is a major sink for atmospheric carbon dioxide, and the subalpine zone stores large amounts of carbon; however, their magnitude and distribution of stored carbon are still unclear.

Results: To clarify the carbon distribution and carbon budget in the subalpine zone at volcanic Jeju Island, Korea, we report the C stock and changes therein owing to vegetation form, litter production, forest floor, and soil, and soil respiration between 2014 and 2016, for three subalpine forest ecosystems, namely, *Abies koreana* forest, *Taxus cuspidata* forest, and *Juniperus chinensis* var. *sargentii* forest. Organic carbon distribution of vegetation and NPP were bigger in the *A. koreana* forest than in the other two forests. However, the amount of soil organic carbon distribution was the highest in the *J. chinensis* var. *sargentii* forest.
Compared to the amount of organic carbon distribution (AOCD) of aboveground vegetation (57.15 t C ha^{-1}) on the subalpine-alpine forest in India, AOCD of vegetation in the subalpine forest in Mt. Halla was below 50%, but AOCD of soil in Mt. Halla was higher. We also compared our results of organic carbon budget in subalpine forest at volcanic island with data synthesized from subalpine forests in various countries.

Conclusions: The subalpine forest is a carbon reservoir that stores a large amount of organic carbon in the forest soils and is expected to provide a high level of ecosystem services.

Keywords: Net primary production, Net ecosystem production, Soil respiration, Carbon cycle

Background

A growing literature is reporting on how the terrestrial carbon cycle is experiencing year-to-year variability because of climate anomalies and trends caused by global change (Baldocchi et al. 2016). Forest ecosystems play a key role in global terrestrial carbon cycle owing to their huge C pool and high productivity (Schlesinger 1997). Forests account for about one third of the land area, and they store about 80% of C from the aboveground terrestrial ecosystem and about 40% of C from the belowground ecosystem in the form of aboveground or belowground biomass, dead tree, litter floor, and soil organic matter (Dixon et al. 1994). Therefore, forest ecosystem serves as an important mediator in balancing atmospheric CO_2 concentration.

In forest communities, biomass per unit area serves as an indicator of material production (Kim 2004; Kim, 2012; Yeochen Ecological Research Society; 2005). Litters are a major route for transportation of stored C from photosynthesis to the soil. Soils in forest ecosystems provide an environment for plants, the primary producers, to grow and store large amounts of carbon (Lee and Son 2006; Vitousek 1991). Soil plays an important role in the circulation of material in a forest ecosystem (Chung et al. 1980). Changes to C stock in the soil, especially where large amounts of carbon are stored, will have a significant impact on the atmospheric carbon

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dioxide concentration. Forest ecosystems in the Northern Hemisphere function as major sinks for atmospheric CO_2 (Battle et al. 2000; Myneni et al. 2001; Goodale et al. 2002). Given that highland forest soils contain five to six times more C than present in peatlands or permafrost soil (Davidson and Jassens 2006), understanding the contribution factors and pursuing research on the underlying mechanisms is highly valuable.

The study area, Mt. Halla, falls under the subalpine zone, and an unusual vegetation type is present because the area is often subjected to typhoon conditions to a greater extent than are other inland subalpine zones (Altman et al. 2012; Kong 2002). These subalpine zones occur at a warmth index less below 4.5 (Lee et al., 2013a, b; Yim 1977). Also Kim (1976) and Kong (2002) referred to the subalpine zone as the timber line, where commercial timber production is possible to the tree line where no trees higher than 4–5 m tall are visible. This tree line has mostly coincided with the average temperature of the warmest month of the year, which happens to be the 10 °C line. Although the subalpine zone at Mt. Halla offers optimal conditions for conducting long-term ecological research to investigate effects of climate change on ecosystems (Song 2011), the *Abies koreana* forest is endemic to Korea, and a rare one; as such, studies on C budget are lacking.

This paper is to provide a synthesis of major C processes and C budgets for *A. koreana* forest, *Taxus cuspidata* forest, and *Juniperus chinensis* var. *sargentii* forest. The major objectives are (1) to evaluate the C sink of these forests and (2) to provide basic data to comprehend the social costs of natural resources that will be caused by climate change through quantitatively analyzing the C budget and distribution of three different forest types in the subalpine zone of Mt. Halla.

Methods

Site

The Jeju Island (1849.02 km^2 in area, 1950 m in altitude) is situated in the southernmost part of South Korea. It has a dormant volcano of basalt and has a warm-temperate climate. Mt. Halla is located in the center of Jeju Island and features a vertical distribution of vegetation based on altitude. Temperate deciduous forests dominate up to 1300 m above sea level. Above this altitude, the subalpine zone appears (Kong 2004). According to climate records at the Korea Meteorological Administration (KMA), the mean annual temperature was 5.77 °C, and the mean annual precipitation was 6828 mm for the study period. The mean temperature slightly increased annually (KMA 2014–2016).

We selected three adjacent forests with different species to minimize the environmental impact. We also selected plots that were located at similar altitudes. Details regarding the study sites are provided in Table 1.

Table 1 General description of experimental sites

Characteristics	Dominant species		
	A. koreana	*T. cuspidata*	*J. chinensis* var. *sargentii*
Latitude	N 33° 21′ 31″	N 33° 21′ 20″	N 33° 21′ 20″
Longitude	E 126° 30′ 27″	E 126° 31′ 01″	E 126° 31′ 02″
Altitude (m)	1660	1648	1651
Density (no./ha)	3700–4100	2200	4000
Mean of soil depth (cm)	20	30	30
Coverage (%)	75	90	95
Mean DBH (cm)	8.72	9.83	4.19
Maximum tree height (m)	5	2	2
SOM (%)	36.27	34.21	34.18

SOM sum organic matter concentration

The *A. koreana* forest was dominated by *A. koreana* trees and accompanied by *Quercus mongolica*, *Prunus maximowiczii*, *Sorbus commixta*, and *Cacalia adenostylodies*. Plants in the understory included *Lycopodium chinense*, *Lycopodium serratum*, *Dryopteris crassirhizoma*, *Taxus cupidata*, and other species. The soil was 20 cm deep, with a Heugag series and high organic matter concentration (36.27%).

The *T. cuspidata* forest was dominated by *T. cuspidata*, accompanied by *Berberis amurensis* var. *quelpaertensis* and *Rhododendron mucronulatum* var. *ciliatum*. Plants in the understory included *Sasa palmata*, *Calamagrostis arundinacea*, *Carex erythrobasis*, *Ligularia fischeri*, *Geranium thunbergii*, and other species. The soil was 30 cm deep, with a Heugag series and high organic matter concentration (34.21%).

The *J. chinensis* var. *sargentii* forest was a shrubbery and a pure community. Herbaceous vegetation was very poor due to the characteristic covering of the ground by this plant. Litter fall on the ground was thin. The soil had a depth of 30 cm, with high organic matter concentration (34.18%).

Study period and plot

The study period was from January 2014 to October 2016. The tree layer forest and shrub land were used with a quadrate of 100–200 m^2 and 9–25 m^2 size, respectively (Yeocheon Ecological Research Society 2005; You et al. 2015; Barbour et al. 1999). As the height of the *A. koreana* forest and *T. cuspidata* forest in the subalpine zone of Mt. Halla was 4 m or less, we used a modified quadrat of 10 × 10 m size, while for the *J. chinensis* var. *sargentii* shrub forest, a quadrat of size 5 × 5 m size was used. This size of quadrat was equal to the size used for Korea Long Term Ecological Research (Ministry of Environment 2013).

Biomass and net primary production

The best method to measure the biomass is the summation method, but felling trees in Mt. Halla is challenging because it has been designated as a national park. Therefore, to measure the biomass of stem and branch of tree layers, we used allometric equations developed using diameter at breast height and biomass of each tree organ (Kittredge 1944). The biomass of leaves and reproductive organ were measured from the litter collected from the litter trap each year. The biomass of shrub layer and herb layer were calculated using the summation method.

In the plot in each forest, all living trees with stem DBH 5 cm or greater were tagged. Tree height and DBH were measured every April. The belowground biomass was estimated to be 25% of the aboveground biomass (Johnson and Risser 1974). Allometric equations used to estimate biomass of tree layer in this study are presented in Table 2.

Net primary production (NPP) was calculated using the difference in biomass during the current year for the next year.

Table 2 Allometric equations for each biomass component against the diameter at breast height (D) and tree height in different tree sizes

Species	*D* range	Allometry		Reference
AK	$1 \leq D < 10$	W_s	$0.00743914(D)_{3.233}$	Wang et al. 2011
		W_{sb}	$0.00394621(D)_{2.799}$	
		Sb	$0.00782838(D)_{2.841}$	
	$10 \leq D < 20$	W_s	$0.01196224(D)_{2.926}$	
		W_{sb}	$0.00714745(D)_{2.549}$	
		Sb	$0.00517974(D)_{2.961}$	
	$20 \leq D$	W_s	$0.13199384(D)_{2.121}$	
		W_{sb}	$0.00088405(D)_{3.169}$	
		Sb	$0.00123708(D)_{3.200}$	
TC		W_s	$0.0361(D_2H)_{0.9184}$	Yasuhiro 2006
		W_b	$0.0155(D_2H)_{0.8979}$	
JC		W_s	$2.639\log(D) - 1.8017$	Kwak et al. 2004
		W_b	$2.334\log(D) - 1.871$	
RS		W	$0.0471(D)_{2.8498}$	Lee et al. 2004
BA		W	$0.0471(D)_{2.8498}$	
PS		W	$0.3421(D)_{2.1813}$	
QM		W	$0.4687(D)_{2.1313}$	
SC		W	$3.54912111643181((D/254)_{2.1657})$	Jennifer et al. 2012

AK Abies koreana, *TC Taxus cuspidata*, *JC Juniperus chinensis* var. *sargentii*, *RS Rhododendron schlippenbachii*, *BA Berberis amurensis* var. *quelpaertensis*, *PS Prunus sargentii*, *QM Quercus mongolica*, *SC Sorbus commixta*, *D* diameter at the breast height, *W* weight, W_s weight of stem, W_{sb} weight of stem bark, W_b weight of branch, *H* height

Amount of organic carbon

The amount of organic carbon of plant biomass was estimated to be 45% of the dry mass (Houghton et al. 1983).

Four smaller quadrate, sized 25 × 25 cm, were installed additionally outside the permanent quadrate in the study site to measure forest floor litter in each season without interference of existing quadrate. The litter was distinguished into L (litter) layer and F (fermentation) layer depending on the degree of decomposition. It was collected separately and measured after being dehydrated at 65 °C in the dryer for more than 48 h in the laboratory. This figure was used to calculate the amount of forest floor litter per unit area (ha).

To investigate the soil depth in each forest before determining the organic carbon stocks in the soil, we measured the soil depth at 20 arbitrary locations in each forest using a 1-m-long iron stick. Soil collection was performed in areas closer to the quadrat that had similar soil properties to the study site because the region had a permanent quadrat installed and the study had to be conducted without disturbing this.

In each forest, soils were collected at 10-cm intervals from three locations outside the permanent square, taking into account the rock ratio and soil depth in the survey area (*A. koreana* forest, 20-cm depth; *T. cuspidate* forest, 30-cm depth, and *J. chinensis* forest, 30-cm depth). The collected soil sample was sealed in a vinyl bag and brought to the laboratory for further analysis.

Air-dried soil (5 g) was weighed after being dehydrated at 105 °C in a dryer for more than 48 h. It was baked in an electric furnace for about 4 h to calculate the amount of organic carbon by subtracting the ash content from the dry weight. The value obtained from subtraction was divided by 1.724 to convert it to organic carbon content equivalents (Black, 1965).

To measure the soil bulk density at 10-cm intervals, we collected the soil using a cylindrical soil sampler (diameter 5 cm and length 5.1 cm). Then, soil samples were sealed and taken to the laboratory for analysis.

The collected soil was dehydrated at 105 °C in a dryer until it reached constant weight and that dry soil weight was divided by the volume to calculate bulk density. The gravel content was measured by filtering gravels from the collected soil using a 2-mm net sieve, and they were weighed to calculate the ratio of gravel weight to the total weight.

The amount of accumulated organic carbon in soil per unit area was calculated from the equation of Wang et al. (2002). This equation was used considering the ratio of gravel.

$$\text{SOC (kg/m}^2) = \text{bulk density (ton/m}^3) \times \text{organic carbon content (g/kg)} \times \text{soil depth (m)} \times (1- \text{gravel ratio})$$

Soil temperature and soil respiration

Soil temperature was automatically monitored hourly during the study period by placing a T&D Thermo Recorder (TR-71) on the top layer of soil (5 cm). The amount of CO$_2$ released into the atmosphere from soil respiration (R) was measured by using the most widely used closed chamber method, equipped with a portable infrared gas analyzer(IRGA; EGM-4 PP system, UK). Of the several methods for measuring R, we chose this method because we could easily measure R using a portable battery in the study area where electricity is not supplied (Elberling and Brandt, 2003; Lee et al. 2010). After removing the litter on the forest floor, we installed a cylindrical chamber (diameter 10 cm, height 15 cm) and attached it to the equipment. We measured R 15 times (3 times at 5 points) per survey in the study area where the crowns overlap. The proportion of root respiration in the R varies from 10 to 90% (Hanson et al. 2000). Root respiration was calculated to be 46% of the total R considering the characteristics of subalpine plants (Koo et al. 2005; Hanson et al. 2000; Jeong et al. 2018).

Results

C distribution

The amount of organic carbon distribution (AOCD) in the vegetation of *A. koreana* forest ranged from 50.48 to 53.33 t C ha^{-1} during 2014–2016, most of which was generated from the trees (50.3–52.46 t C ha^{-1}). Most of the C in trees was stored in the aboveground biomass. Vegetation had higher AOCD than soil stores; AOCD of soil at 20-cm depth was between 39.97 and 43.05 t C ha^{-1}, and AOCD for the forest floor ranged between 1.45 and 1.87 t C ha^{-1}. The total AOCD of *A. koreana* forest ranged from 142.8 to 151.44 t C ha^{-1} (Table 3).

AOCD of vegetation of *T. cuspidata* forest ranged from 15.44 to 16.98 t C ha^{-1} during 2014–2016, most of which also came from trees (15.37–16.83 t C ha^{-1}). Most of the C in trees was also stored in the aboveground biomass. AOCD was higher in the soil than in the vegetation; AOCD of soil at the 30-cm depth was between 121.4 and 144.07 t C ha^{-1}. Total AOCD of *T. cuspidata* forest ranged from 168.07 to 171.17 t C ha^{-1} (Table 3).

AOCD of vegetation of *J. chinensis* var. *sargentii* forest ranged from 3.24 to 4.4 t C ha^{-1} during 2014–2016, most of which came from trees (3.34–4.4 t C ha^{-1}). Most of the C in trees was stored in the aboveground biomass. AOCD was higher in the soil than in the vegetation; AOCD of soil at 30-cm depth was between 160.6 and 161.49 t C ha^{-1}. The total AOCD of *J. chinensis* var. *sargentii* forest ranged from 168.07 to 199.66 t C ha^{-1} (Table 3).

Soil respiration

The temperature of the soil at 5 cm in the three forests is shown in Fig. 1. The soil temperature in study sites increased during the study period. The coefficient between R and soil temperature at 5-cm depth for *A. koreana*, *T. cuspidata*, and *J. chinensis* var. *sargentii* was 0.777, 0.854, and 0.806 g m^{-2} h^{-1}, respectively (Fig. 2). Extrapolating the soil at 5-cm depth to the regression equation showed that the R was the highest in *A. koreana* forest and the lowest in *J. chinensis* var. *sargentii* forest (Table 4).

Table 3 AOCD (t C ha^{-1}) of each forest in the subalpine zone, Jeju Island, Korea

Item	*A. koreana* forest			*T. cuspidata* forest			*J. chinensis* var. *sargentii* forest*		
	2014	2015	2016	2014	2015	2016	2014	2015	2016
Vegetation	50.48	50.67	53.33	15.44	15.78	16.98	3.34	3.62	4.4
Tree	50.3	50.34	52.46	15.37	15.69	16.83	3.34	3.62	4.4
Stem	30.29	29.79	30.78	8.58	8.69	8.9	1.45	1.47	1.58
Branch	9	8.66	8.89	2.69	2.72	2.78	0.76	0.78	0.82
Leaf+Rep.	0.95	1.83	2.3	1.03	1.14	1.78	0.46	0.65	1.12
Root	10.06	10.06	10.49	3.07	3.14	3.37	0.67	0.72	0.88
Shrub	0.14	0.23	0.48	–	–	–	–	–	–
Herb	0.04	0.1	0.39	0.07	0.09	0.15	–	–	–
Floor	1.87	1.45	1.73	0.87	0.84	0.75	0.89	1.04	0.88
L-layer	1.02	0.79	0.8	0.48	0.49	0.41	0.61	0.69	0.53
F-layer	0.85	0.66	0.93	0.39	0.35	0.34	0.28	0.35	0.35
Soil	39.97	43.58	43.05	121.4	138.27	144.07	160.6	191.38	161.49
10 cm	23.38	24.65	23.31	42.72	56.87	57.71	58.43	70.13	60.09
20 cm	16.59	18.93	19.74	40.71	42.73	44.12	53.60	64.86	52.66
30 cm	–	–	–	37.97	38.67	42.24	48.57	56.39	48.74
Total	142.8	146.37	151.44	153.15	170.67	178.78	168.07	199.66	171.17

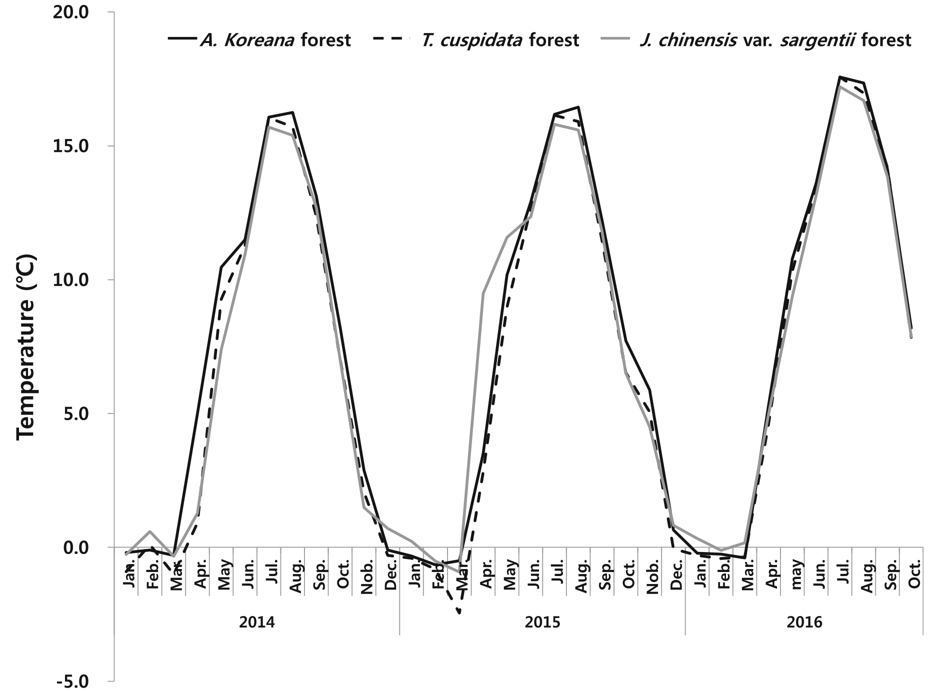

Fig. 1 Monthly fluctuation in temperature of soil at 5-cm depth in the forest ecosystems in the subalpine zone, Jeju Island, over multiple years. The three lines represent the temperature of soil at 5-cm depth in each forest (black solid line, *A. koreana* forest; black dotted line, *T. cuspidata* forest; gray solid line, *J. chinensis* var. *sargentii* forest)

C flux

In 2014 and 2015, litter production (*L*) in *A. koreana* forest was 1.36 and 2.1 t C ha^{-1}, respectively. NPP was 2.41 and 3.81 t C ha^{-1}, respectively. *R* was 6.46, from 3.49 and 2.97 t C ha^{-1} for heterotrophic and root parts, and 6.85, with 3.7 and 3.15 t C ha^{-1} for heterotrophic and root parts, respectively. Therefore, net ecosystem production (NEP) of this forest in 2014 and 2015 is estimated as − 1.08 and 0.11 t C ha^{-1}, respectively (Table 4).

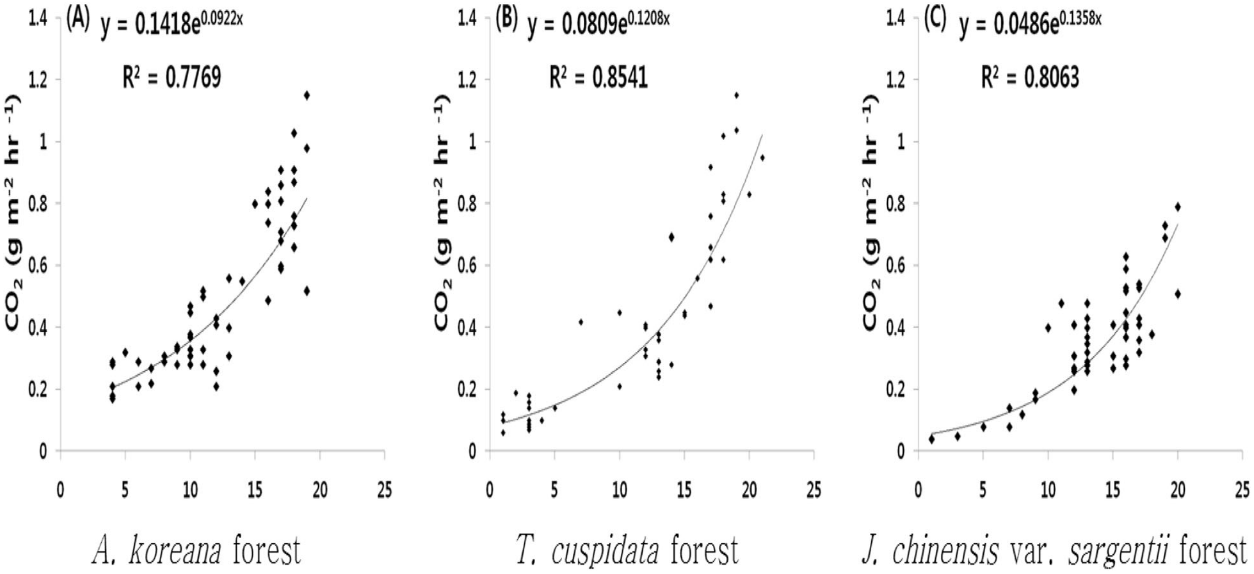

Fig. 2 Relationship between soil respiration (g m^{-2} h^{-1}) and soil temperature (℃) at 5-cm depth in three subalpine forest ecosystems (**a**: A koreana forest, **b**: T. cuspidata forest, **c**: J. chinensis var. sargentii forest)

Table 4 C fluxes (t C ha^{-1}). NEP was calculated as the difference between the amount of net organic carbon absorbed from the atmosphere and the amount of heterotrophic respiration in the released soil respiration. Litter production refers to the amount of organic carbon injected clinically through litters

Item	*A. koreana* forest		*T. cuspidata* forest		*J. chinensis* var. *sargentii* forest	
	2014	2015	2014	2015	2014	2015
Litter production	1.36	2.1	1.3	1.46	0.53	0.75
Wood	0.23	0.27	0.25	0.32	0.06	0.06
Leaf	0.94	1.76	0.9	1.04	0.43	0.64
Rep. organ	0.1	0.07	0.13	0.1	0.03	0.01
Others	0.09	0	0.02	0	0.01	0.04
NPP	2.41	3.81	1.31	1.73	0.55	0.96
Soil respiration	6.46	6.85	4.83	5.01	3.55	4.09
Heterotrophic	3.49	3.7	2.61	2.71	1.92	2.21
Root	2.97	3.15	2.22	2.3	1.63	1.88
NEP	− 1.08	0.11	− 1.3	− 0.98	− 1.37	− 1.25

In 2014 and 2015, *L* of *T. cuspidata* forest was 1.3 and 1.46 t C ha^{-1}, respectively. NPP was 1.31 and 1.73 t C ha^{-1}, respectively. *R* was 4.83, from 2.61 and 2.22 t C ha^{-1} for heterotrophic and root parts, and 5.01, from 2.71 and 2.3 t C ha^{-1} for heterotrophic and root parts, respectively. Therefore, NEP of this forest in 2014 and 2015is estimated as − 1.3 and − 0.98 t C ha^{-1}, respectively (Table 4).

In 2014 and 2015, *L* of *J. chinensis* var. *sargentii* forest was 0.53 and 0.75 t C ha^{-1}, respectively. And NPP was 0.55 and 0.96 t C ha^{-1}, respectively. *R* was 3.55, from 1.92 and 1.63 t C ha^{-1} for heterotrophic and root parts, and 4.09, from 2.21 and 1.88 t C ha^{-1} for heterotrophic and root parts, respectively. Therefore, NEP of this forest in 2014 and 2015 is estimated as − 1.37 and − 1.25 t C ha^{-1}, respectively (Table 4).

C budget

We constructed the C budgets for subalpine forest ecosystems as shown in Fig. 3. Vegetation refers to the tree, shrub, and herb layers. *A. koreana* forest had the largest amount of organic carbon fixed to the vegetation, with a higher NPP compared to the other forests. However, the amount of organic carbon spilled into the atmosphere, primarily through *R* was also the highest. This result means that the *A. koreana* forest circulated the most organic carbon during the 2014–2015 study period.

Discussion

C distribution

The AOCD of three different forests increased year over year. The AOCD of tree layers in the *A. koreana* forest showed no significant changes for 2014 and 2015. This is because four small trees died in the 2015. Among the three forests, AOCD of vegetation in *A. koreana* forest was the highest, while it was lowest in *J. chinensis* var. *sargentii* forest. AOCD of vegetation in subalpine forests, which are relatively short, is typically much lower than in lowland forests (Jang 2017). AOCD of vegetation increases proportionately to plant height because trees tend to store most of the C in their stem. In particular, the average height of vegetation in Mt. Halla was lower than other similar forests because the soil is not deep

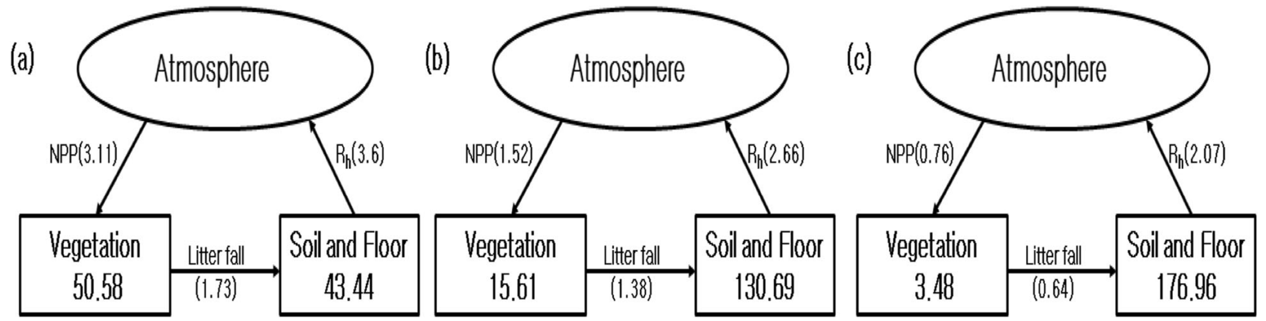

Fig. 3 Carbon budgets of three subalpine forest ecosystems in Mt. Halla, Korea. **a** *A. koreana* forest. **b** *T. cuspidata* forest. **c** *J. chinensis* var. *sargentii* forest. The values in parentheses represent flux (t C ha^{-1}), while the other values represent the pools (t C ha^{-1})

(JSSGP 2008; Jang 2017) and is impacted by typhoons, compared to other regions (Altman et al. 2012).

Compared to the AOCD of the aboveground vegetation (57.15 t C ha^{-1}) on the subalpine-alpine forest in India, AOCD of vegetation in the subalpine forest in Mt. Halla was below 50%. Also, the AOCD (35–50 t C ha^{-1}) of vegetation in subalpine forest of Mt. Dongling in China (Fang et al. 2007) was higher than that of the subalpine zone of Mt. Halla. The AOCD of soil in *T. cuspidata* forest (130.69 t C ha^{-1}) and *J. chinensis* var. *sargentii* forest (176.96 t C ha^{-1}) were higher than the AOCD of brown earth soil in China (97.1 t C ha^{-1}) (Wu et al. 2003), as well as the global mean AOCD (106 t C ha^{-1}) (Foley 1995). The AOCD of soil in *A. koreana* forest (43.44 t C ha^{-1}) was relatively lower compared to the other forests. AOCD of soil at 1-m depth (209–244 t C ha^{-1}) in Mt. Dongling, China, was higher than that observed in this study. This may be due to the fact that soil at depths of 50–100 cm were considered in other studies, but soil depth of 20 cm was used for evaluating *A. koreana* forest at Mt. Halla.

The AOCD of the aboveground vegetation in the *Picea abies* forest (1740 m) in the Alps was 54 t C ha^{-1}, and the AOCD of soil at 30-cm depth was 115 t C ha^{-1}. Although the AOCD of vegetation was higher than that in this study, only a small amount of the AOCD was accumulated in the soil (Rodeghiero and and Cescatti 2005).

Considering this soil depth, it appears that the soil of Mt. Halla stored very high organic carbon. For this reason, most carbon in the subalpine forest is in the form of humus atop or in the surface soil. This is because acidic, cold soils are not favorable to decomposers. The allocation of net production to different organs also differs from forest to forest. Grassland communities channel much of their energy to belowground biomass, while scrub communities apportion even lesser amounts to belowground, and forests even lesser (Barbour et al. 1999).

In this study, other environmental factors were minimized by selecting the three different forest types located adjacent to each other. However, the AOCD was found to be different, and varied according to vegetation type even though the environmental conditions were similar.

Several studies have attempted to generalize the AOCD in forests in a variety of ways, but in order to estimate AOCD in forests, elevation, soil depth, soil temperature, and forest vegetation types should be considered.

Soil respiration

During the study period, the temperature of soil at 5-cm depth increased every year. This was also the case with air temperature according to the Korea Meteorological Administration, located adjacent to the study site (KMA 2014-2016). Considering the temperature of soil at 5-cm depth in November and December 2016, which were not measured, the temperature of soil at 5-cm depth steadily increased from January to October.

The amount of *R* of the three study forests has a high correlation with soil temperature (Fig. 2). Our results show that soil temperature is an important factor of *R* and has a tendency similar to many other research results and it is similar to the *R* regression equation in lowland forests (Jang 2017; Jeong 2015; Pyo et al. 2003).

During the study period, the amount of organic carbon released to the atmosphere through *R* increased as the soil temperature of each forest increased year by year.

C flux

NPP of the three subalpine forests in Mt. Halla, Jeju Island, ranged from 0.55 to 3.81 t C ha^{-1} during 2014–2016, suggesting that the tree, shrub, and herb layers contain organic carbon. *A. koreana* forest (1.73 t C ha^{-1}) had higher NPP and higher *L* than *T. cuspidata* forest (1.38 t C ha^{-1}) and *J. chinensis* var. *sargentii* forest (0.64 t C ha^{-1}). This result, except for the shrub *J. chinensis* var. *sargentii* forest, is comparable to that of the three subalpine forests (1.63–2.34 t C ha^{-1}) in China (Fang et al. 2007). However, subalpine forests, including this study, had very low C compared to the NPP and *L* in the Korean lowland coniferous forests (Park and Lee 1990; Lee 2011; Lee et al., 2013a, b).

R, mainly through heterotrophic respiration, was estimated as 3.6, 2.66, and 2.07 t C ha^{-1} for *A. koreana*, *T. cuspidata*, and *J. chinensis* var. *sargentii* forests, respectively, which was very much lower than that of forests in the lowland of landward region (Kang et al. 2003; Moon 2004).

NEP is defined as NPP minus R_h and has been suggested to be a direct measure of C exchange between the atmosphere, the ecosystem, and C source/sink in the ecosystem (Schlesinger 1997; Schulze et al. 2000; Chapin et al. 2002). We found that the NEP differed among the three subalpine forest ecosystems studied.

The NEP varied from larger and smaller level every year, and the NEP in the study area was generally lower than that in other subalpine forests (Table 5). Also, in subalpine zone at Mt. Halla, Korea, NEP was relatively low compared to other low altitude forests(Brown et al. 2009; Jeong 2015; Lee et al., 2013a, b; Lee et al. 2015; Pyo et al. 2003; Hong 2012). This is because the height of the vegetation is small due to the strong wind effect and low effective soil depth.

C fluxes of *J. chinensis* var. *sargentii* forest correspond to the C fluxes of tundra region when compared to the global vegetation types (Larcher 1995). In this forest, scattered *Empetrum nigrum* var. *japonicum* plants that are common in the Tundra region were seen, and shrubs with a plant height of less than 1 m are dominant.

Table 5 Comparison of NEP (t C ha^{-1} year^{-1}) at the subalpine zone according to altitude, year, and community type

Regions	Latitude	Elevation	Community	Year	NEP	Reference
Korea			*AK*	2014	– 1.08	This study
		1660		2015	0.11	
			TC	2012	– 1.74	Jang 2017
	33° 21	1648		2014	– 1.3	This study
				2015	– 0.98	
			JC	2014	– 1.37	This study
		1651		2015	– 1.25	
USA	41° 22	3186	*PE + AL*	1996	1.95	Zeller and Nikolov 2000
				1999	0.81	
				2000	0.58	
	40° 1′	3050	*AL*	2001	0.68	Monson et al. 2005
				2002	0.14	
				2003	0.61	
Switzerland	46° 48	1639	*PA*	1997–2011	0.54–3.36	Zielis et al. 2014
Italy				2009	0.67	
	45° 50	2160	*GL*	2010	0.58	Galvagno et al. 2013
				2011	1.21	
	41° 52	1720	*M,C*	1998	4.5	
	46° 18	1560	*BD*	1996	6.6	Valentini et al. 2000
		1560	*BD*	1993	4.7	
China	37° 29	3250	*GL*	2002	0.79	Kato et al. 2004
		1350	*BP*	1994	0.95	
	39° 58	1150	*QL*	1994	– 0.29	Fang et al. 2007
		1050	*PT*	1994	4.08	

AK Abies koreana, TC Taxus cuspidata, JC Juniperus chinensis var. *sargentii, PE Picea engelmanni, BD* broad-leaved deciduous, *BP Betula platyphylla, QL Quercus liaotungensis, PT Pinus tabulaeformis, AL A. lasiocarpa, PA Peicea abies, GL* grassland

However, completely different plant types were found to be distributed in the *A. koreana* forest and *T. cuspidata* forest located adjacent to the *J. chinensis* var. *sargentii* forest.

Carbon budget is known to vary depending on various factors such as time and space (Mukhortova et al. 2015). Even though adjacent forests' geographical locations, soil condition, and climatic conditions are similar, the results of this study show that the carbon budget of the forests can be largely different depending on the dominant vegetation type of the forests.

Conclusions

Based on 3-year measurement of all major components and processes of C budget, we constructed C budgets for three subalpine forest ecosystems in Mt. Halla, Korea (Fig. 3). The main conclusions are summarized as follows:

(1) Total C distribution ranged from 94.02 to 180.44 t C ha^{-1} for three forest ecosystems (*A. koreana*, *T. cuspidata*, and *J chinensis* var. *sargentii* forests), with 50.58–93.48 t C ha^{-1} in vegetation and 43.44–176.96 t C ha^{-1} in soil (including forest floor), suggesting large differences in C distribution among these forests. Even in adjacent forests, differences in the C distribution in forests were observed as when vegetation types differed.

(2) During the study period (1992–1994), NPP of all three forests increased, with a net increment of 0.76–3.11 t C ha^{-1}. L and $R_{\rm h}$ were estimated as 0.64–1.73 t C ha^{-1} and 2.07–3.6 t C ha^{-1}, respectively. Generally, all three forests experienced an increase in biomass.

(3) As a result, we conclude that the subalpine ecosystem functions weakly as C sinks but provides a very high ecosystem service as a carbon pool. In addition, this result cannot be simply extended to other ecosystems because it provides research data over a relatively short period (2014–2016) only.

Abbreviations

AOCD: Amount of organic carbon distribution; *L*: Litter production; NEP: Net ecosystem production; NPP: Net primary production; *R*: Soil respiration

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Authors' contributions

All authors conducted a survey together during the study period. JRH wrote the manuscript. YYH participated in the design of the study and examined the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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