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Soil CO_2 efflux in a warm-temperature and sub-alpine forest in Jeju, South Korea

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Abstract

Background: This study investigated the temporal variation in soil CO_2 efflux and its relationship with soil temperature and precipitation in the *Quercus glauca* and *Abies koreana* forests in Jeju Island, South Korea, from August 2010 to December 2012. *Q. glauca* and *A. koreana* forests are typical vegetation of warm-temperate evergreen forest zone and sub-alpine coniferous forest zone, respectively, in Jeju island.

Results: The mean soil CO_2 efflux of *Q. glauca* forest was 0.7 g CO_2 m^{-2} h^{-1} at 14.3 °C and that of *A. koreana* forest was 0.4 g CO_2 m^{-2} h^{-1} at 6.8 °C. The cumulative annual soil CO_2 efflux of *Q. glauca* and *A. koreana* forests was 54.2 and 34.2 t CO_2 ha^{-1}, respectively. Total accumulated soil carbon efflux in *Q. glauca* and *A. koreana* forests was 29.5 and 18.7 t C ha^{-1} for 2 years, respectively. The relationship between soil CO_2 efflux and soil temperate at 10 cm depth was highly significant in the *Q. glauca* ($r^2 = 0.853$) and *A. koreana* forests ($r^2 = 0.842$). Soil temperature was the main controlling factor over CO_2 efflux during most of the study period. Also, precipitation may affect soil CO_2 efflux that appeared to be an important factor controlling the efflux rate.

Conclusions: Soil CO_2 efflux was affected by soil temperature as the dominant control and moisture as the limiting factor. The difference of soil CO_2 efflux between of *Q. glauca* and *A. koreana* forests was induced by soil temperature to altitude and regional precipitation.

Keywords: CO_2 efflux, Soil temperature, Precipitation, *Abies koreana*, *Quercus glauca*, Jeju island

Background

Soil respiration is one of the processes in the ecosystem that comprises root respiration, decomposition of soil organic matters by microorganisms, and efflux of CO_2 from the animals (Luo and Zhou 2006). It plays an important role in the regulation of carbon cycle in regional and global scale. Carbon cycle in global scale consists of exchange of CO_2 between biome on land, atmosphere, and ground surface. The terrestrial plants absorb about 120 Pg of carbon each year through photosynthesis, and it is recycled into the atmosphere through respiration in the ecosystem. The soil around the world contains 3150 Pg of carbon; 450 Pg C in wetlands, 400 Pg C in tundra, and 2300 Pg in other ecosystem (Sabine et al. 2004). It is known that other ecosystems contain 1500 Pg C up to 1 m and 800 Pg C up to 3 m in soil depth (Jobbagy and Jackson 2000). The sum of carbon in plants and soil, which is 3800 Pg C, is five times more than the carbon distributed in the atmosphere (750 Pg C) because the plants also contain 650 Pg C carbon. Furthermore, carbon is also in every living organism as the primary component (Kim et al. 2014). The plants make organic compounds using CO_2, water, and sunlight where light energy is stored in organic compounds through photosynthesis. The organic compounds are used by plants themselves in respiration and some become part of the plant. They ultimately carry out crucial roles in the ecosystem, for example, in net production and keeping the carbon balance.

Net ecosystem production (NEP), which shows net gain or loss of carbon in the ecosystem, should be analyzed in order to accurately estimate the carbon balance in the forest ecosystem. NEP can be obtained by subtracting the amount of organic matter consumed by heterotrophic respiration from net primary productivity (NPP), and studies are being carried out recently to accurately forecast the amount of CO_2 released from heterotrophic respiration of soil (Nakane 1995, Raich and Tufekcioglu 2000, Lee and Mun 2001, Lee et al. 2012).

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The subject of this study, *Quercus glauca*, an evergreen broad-leaved tree, and *Abies koreana*, an evergreen coniferous tree, are typical vegetation distributed in warm-temperate forest and sub-alpine forest found in Korea. Warm-temperate forest is a narrow vegetation belt found between tropical and temperate forest zones. It is mainly located along southern coastlines and island regions that have average annual temperature above 14 °C and following vegetation are found: *Castanopsis cuspidata*, *Machilus thunbergii*, *Q. glauca*, *Camellia japonica*, *Cinnamomum japonicum*, *Euonymus japonicus*, *Trachelospermum asiaticum*, *Stauntonia hexaphylla*, etc. (Kong 2007). The distribution of warm-temperate evergreen broad-leaved forests in Korea has increased by approximately 2.7 times over the past 20 years, and it is expected to move up to northern regions in the future (Park et al. 2010). On the other hand, evergreen coniferous forests are found in boreal zones, such as plateau or alpine region that has an average annual temperature below 5 °C with average temperature of −12 °C during January. Trees that have adapted to cold winter and short growing period, such as *Abies holophylla*, *Picea jezoensis*, *A. nephrolepis*, *Pinus koraiensis*, *A. koreana*, *Larix gmelinii*, *Betula costata*, and *B. platyphylla*, are usually found in this region (Kong 2007). The study result on the community structure of *A. koreana* distributed around Mt. Halla revealed low vitality of *A. koreana* in the area with up to 8.11% frequency of dead trees (Kim et al. 1998). In fact, there are studies that claim plants that belong to genus *Abies*, which are main species of sub-alpine and sub-polar zone, will slowly become decline due to global warming (Kim 2002, Koo et al. 2001, Kong 1998, Kim and Kil 1996).

The study area is a forest ecosystem that is expected to respond sensitively to climate change caused by global warming. *Q. glauca* community is expected to expand, but *A. koreana* community is expected to decline. The sub-alpine vegetation of Mt. Halla, where *A. koreana* community is located, especially is vulnerable to high winter temperatures and water stress caused by global warming, and thus affects plant productivity and soil CO_2 efflux, which results in a change in the NEP of sub-alpine vegetation. Soil CO_2 efflux plays a crucial role in controlling atmospheric CO_2 concentrations and climate change in the global ecosystem.

In addition, the importance of soil respiration should be emphasized for the accurate measurement of carbon balance in the changing forest ecosystem. The purpose of this study is to provide basic data and to analyze the features of soil respiration according to temperature in *Q. glauca* community and *A. koreana* community which are the main forest ecosystem in warm-temperate and sub-alpine zone.

Methods

Site description

This study was conducted on *Q. glauca* community and *A. koreana* community located in Jeju island (Fig. 1). *Q. glauca* community (33° 31′ 09″ N, 126° 42′ 57″ E) was distributed around Mt. Dongbaek situated in Sunheul-ri, Jocheon-eup, Jeju island. More than 10% of evergreen broad-leaved forests in this island are found in this area which is a Gotjawal terrain (Kwak et al. 2013). The stand age in *Q. glauca* community was about 38 years, and evergreen vegetation, such as *Camellia japonica*, *Eurya japonica*, and *Ardisia japonica*, inhabited the herb layer of the community (Table 1). The average annual temperature and precipitation of Sunheul-ri in Jocheon-eup, where *Q. glauca* community is distributed, were 13.2 °C and 2447 mm respectively during the study period. *A. koreana* community (33° 21′ 31″ N, 126° 30′ 27″ E)

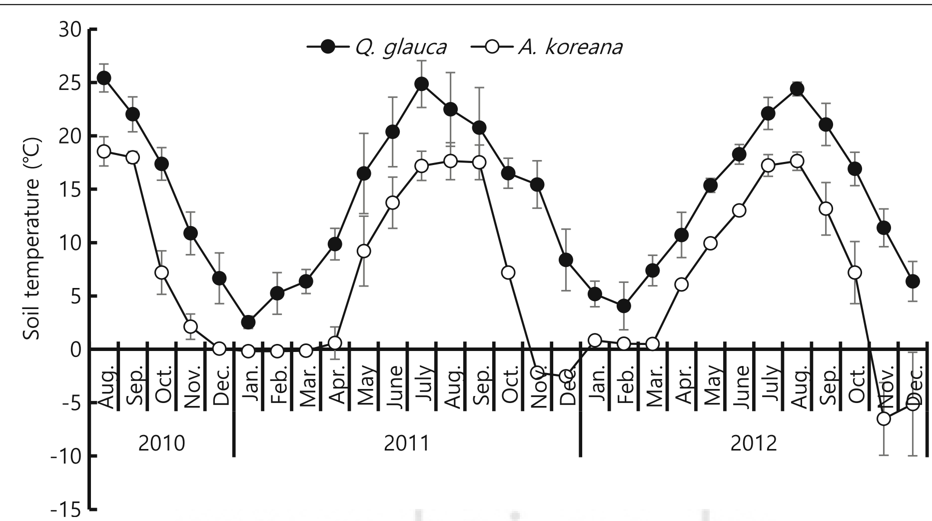


Fig. 1 Monthly variation of soil temperature at 10 cm depth below ground in *Q. glauca* and *A. koreana* communities

Table 1 Habitat characteristics of the *Q. glauca* and *A. koreana* communities

Study forest		
Characteristics	*Q. glauca*	*A. koreana*
Altitude (m)	126	1660
Density (tree/ha)	16,000	3700
Forest age (year)	38	90
Tree layer		
Dominant species	*Q. glauca*	*A. koreana*
Tree height (m)	16	7
Mean DBH (cm)	7.4	9.5
Coverage (%)	90	85
Shrub layer		
Dominant species	*Eurya japonica*	*Taxus cuspidata*
	Camellia japonica	*Rhododendron mucronulatum*
	Q. glauca	*Symplocos coreana*
Shrub height (m)	2	0.8
Coverage (%)	15	10
Herb layer		
Dominant species	*Ardisia japonica*	*Empetrum nigrum*
	Q. glauca	*Sasa quelpaertensis*
Herb height (m)	0.45	0.3
Coverage (%)	45	50

was distributed in Youngsil region with altitude of 1400 m above sea level around Mt. Halla. The stand age in *A. koreana* community was about 90 years, and sub-alpine vegetation, such as *Taxus cuspidate*, *Rhododendron mucronulatum*, *Empetrum nigrum*, and *Sasa quelpaertensis*, were found in the herb layer of the community. The average annual temperature and precipitation of Witseorum of Youngsil in Mt. Halla, where *A. koreana* community is distributed, were 6.1 °C and 5882 mm respectively. The difference in altitude and average annual temperature of *Q. glauca* community and *A. koreana* community were 1500 m and 7.1 °C representing warm-temperate and sub-alpine forest that has contrasting climate and ecosystem.

Measurement of soil temperature and respiration

Measurements of soil respiration efflux were taken in all seasons to take into account its characteristics at various temperature ranges, and measurement was conducted between 10 am and 4 pm on a clear day. For each vegetation community, soil respiration efflux was measured ten times at three random sites in the quadrate, and the maximum and minimum values were excluded from the analysis.

The soil respiration was measured by using IRGA portable gas analyzer (EGM4, PP System, UK). The soil temperature at 10 cm depth after removing litterfall and CO_2 efflux was measured over the whole year throughout four seasons in order to clearly understand the relationship between soil temperature, respiration, and CO_2 efflux. Digital thermometers (Thermo recorder TR-71U, T&D Co., Japan), respectively, were placed 10 cm below ground, and the temperature was recorded every hour in order to measure the soil temperature of *Q. glauca* community and *A. koreana* community from August 2010 to December 2012.

Data treatment and analysis

A regression equation for the relationship between soil temperature and CO_2 efflux was derived from the data on CO_2 efflux of *Q. glauca* community and *A. koreana* community which was obtained by using the infrared gas analyzer and their soil temperature 10 cm below ground. The data on soil temperature gathered from digital thermometers installed 10 cm below ground in each community was substituted into the regression equation to calculate CO_2 efflux per hour. Furthermore, based on these results, the annual and monthly soil respiration and the amount of carbon emissions from forests were estimated.

Results and Discussion

Monthly variations of soil temperature

The average monthly soil temperature of *Q. glauca* community was 14.3 °C during the study period (Fig. 2). It was 14.1 °C in 2011 and 13.6 °C in 2012. The soil temperature of *Q. glauca* community was the highest in August 2010 reaching 25.4 °C and lowest in January 2011 going down to 2.5 °C. Soil temperature was generally low from January to February, but it was high from July to August. However, it never decreased below 0 °C during the study period. The average monthly soil temperature of *A. koreana* community was 6.8 °C during the study period. It was 6.5 °C in 2011 and 6.2 °C in 2012. The soil temperature of *A. koreana* community was the highest in August 2010 reaching 18.5 °C and lowest in November 2012 going down to −6.5 °C. Soil temperature was generally low from November to April, but it was high from July to September. The temperature difference between the warmest and coldest month was greater in 2012 than 2011.

Soil CO_2 efflux analysis

The soil CO_2 efflux of *Q. glauca* community and *A. koreana* community measured by the infrared gas analyzer was formulated into an exponential equation showing positive relationship (Fig. 3). Nonetheless, the exponential CO_2 efflux according to temperature was the same as the existing study (Chen et al. 2013, Darenova et al. 2014). Soil CO_2 efflux was greater in *A. koreana* community than *Q.*

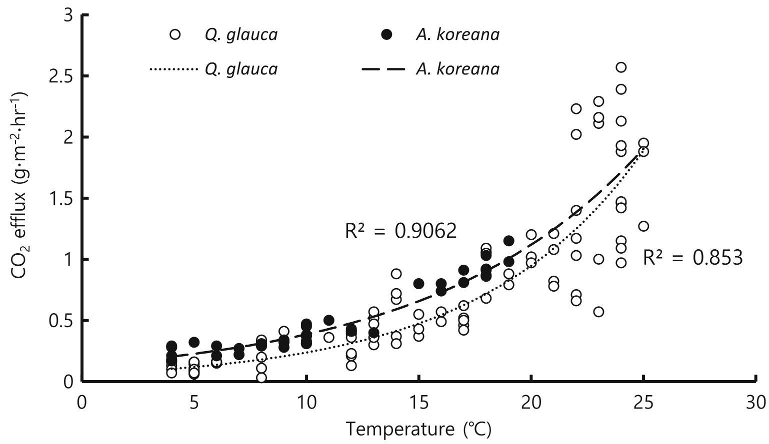


Fig. 2 The relationship between soil respiration and the temperature at 10 cm depth below ground in the *Q. glauca* and *A. koreana* communities

glauca community in all the temperature range. A significant increase in soil CO_2 efflux depending on an increase in the soil temperature in the *Q. glauca* community and *A*. koreana community is related to the biochemical activity of heterotrophs in the soil, and it is known that there is generally an exponential relation between soil CO_2 efflux and soil temperature (Luo and Zhou 2006).

Coefficient of determination (R^2) of the regression equation for soil CO_2 efflux and temperature of *Q. glauca* community and *A. koreana* community was of 0.853 and 0.8419 respectively (Table 2). CO_2 efflux from *Q. glauca* community and *A. koreana* community decreased in winter but increased in summer because soil respiration fluctuates with change in temperature (Fig. 4). Soil respiration of *Q. glauca* community was the lowest over January and February whereas it was the highest in July 2011 and August 2012. On the other hand, soil respiration of *A. koreana* community was the lowest from December 2010 to April 2011, from November 2011 to March 2012, and from November 2012 to December 2012 whereas it was the highest in July 2011 and August 2012. *Q. glauca* community and *A. koreana* community had similar lowest monthly CO_2 efflux of about 0.1 g m^{-2} h^{-1}, but it lasted over about 2 months in *Q. glauca* community and about 5~6 months in *A. koreana* community over a year. The highest monthly CO_2 efflux of Q. glauca community was 2.1 g m^{-2} h^{-1} in 2011 and 2.0 g m^{-2} h^{-1} in 2012 whereas *A. koreana* community was 0.8 g m^{-2} h^{-1} in 2011 and 0.9 g m^{-2} h^{-1} 2012. It lasted for a month in both communities in 2011 as well as in 2012. The average monthly CO_2 efflux of *Q. glauca* community was 0.7 g m $^{-2}$ h^{-1}, and *A. koreana* community was 0.4 g m^{-2} h^{-1} during the study period. *Q. glauca* community was about 1.8 times greater than *A. koreana* community. This was caused by the difference in the soil temperature of *Q. glauca* community and *A. koreana* community. CO_2 efflux of *Q. glauca* community over July and August is two times greater than *A. koreana* community due to high soil temperature, but CO_2 efflux of *A. koreana* community is kept at its lowest level from November to March due to low soil temperature. It is presumed that the difference in soil temperature is based on the altitude of *Q. glauca*

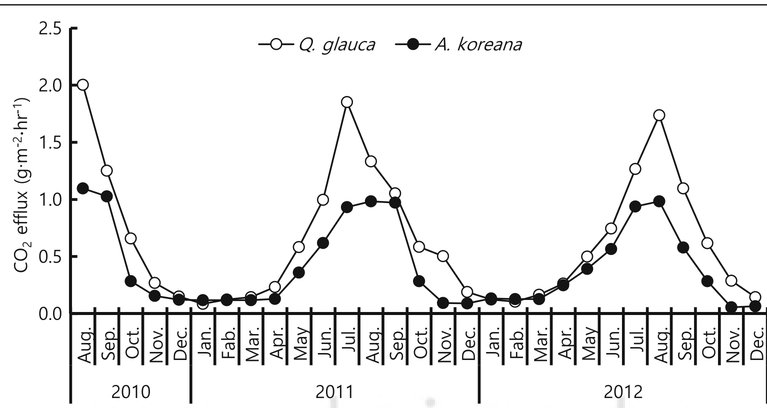


Fig. 3 Monthly variations of CO_2 efflux (g CO_2 m^{-2} h^{-1}) in the *Q. glauca* and *A. koreana* communities

Table 2 Comparison of exponential equations relation to soil respiration and temperature

Community	Equation	a	b	R^2
Q. gluaca	$y = ae^{bx}$	0.0598	0.1381	0.853
A. koreana	$y = ae^{bx}$	0.1201	0.1193	0.8419

a, b are parameters and y, x refers to soil respiration and temperature, respectively

community and *A. koreana* community. This result was the same as that of Kane et al. (2003) which showed a decrease in soil temperature and respiration with increase in altitude even within the same region.

Annual CO_2 efflux of *Q. glauca* community was 56.4 t CO_2 ha^{-1} in 2011, 51.9 t CO_2 ha^{-1} in 2012, and the average was 54.2 t CO_2 ha^{-1} (Table 3). Annual organic carbon efflux was 15.4 t C ha^{-1} in 2011, 14.1 t C ha^{-1} in 2012, and the average was 14.8 t C ha^{-1}. Annual CO_2 efflux of temperate deciduous forest and tropical rainforest is known to range from 4.0 to 10.0 t C ha^{-1} and 8.9 to 15.2 t C ha^{-1} respectively (Raich and Schlensinger 1992, Luo et al. 2006). The average organic carbon efflux of *Q. glauca* community, which is 14.8 t C ha^{-1}, is included in the annual CO_2 efflux range of tropical rainforest. Soil organic carbon efflux of *Q. robur L.* community, a temperate deciduous forest, in Belgium was 6.9 t C ha^{-1} (Yuste et al. 2005), and *Q. mongolica* community, one of main forest ecosystems in Korea, was 7.7 t C ha^{-1} (Yi et al. 2005) which were greater than the soil organic carbon efflux of *Q. glauca* community.

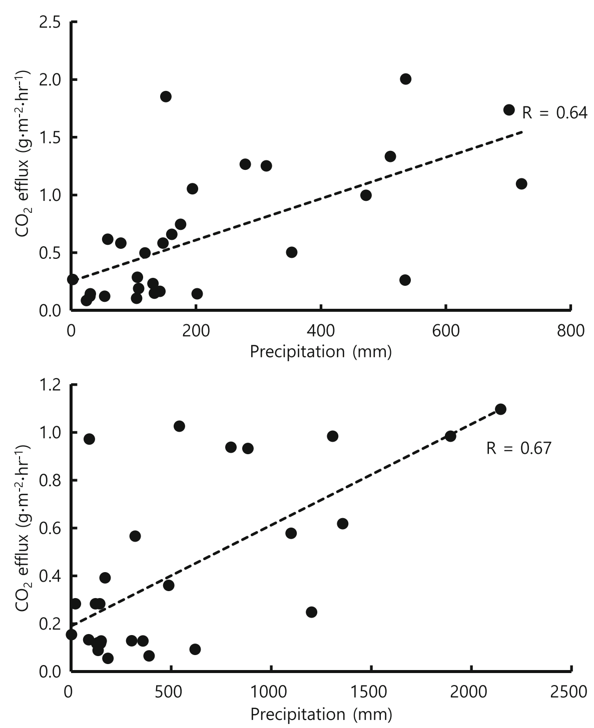


Fig. 4 The correlation between precipitation and modeled soil CO_2 efflux in the *Q. glauca* (above) and *A. koreana* (below) from in August 2010 to December 2012

Annual CO_2 efflux of *A. koreana* community was 35.3 t CO_2 ha^{-1} in 2011, 33.1 t CO_2 ha^{-1} in 2012, and the average was 34.2 t CO_2 ha^{-1} (Table 3). In addition, annual organic carbon efflux was 9.6 t C ha^{-1} in 2011, 9.0 t C ha^{-1} in 2012, and the average was 9.3 t C ha^{-1}. The annual carbon emissions of the *Taxus cuspidate* community in the sub-alpine vegetation area of Mt. Halla in 2012 were 2.9 t CO_2 ha^{-1} (Jang et al. 2017), and they were less than the annual carbon emissions of the *A. koreana* community in Mt. Halla studied during the same period in 2012 (9.0 t CO_2 ha^{-1}).

Average soil CO_2 efflux of *A. koreana* community was greater in this case as the annual soil respiration in alpine zone is generally known to range from 1.5 to 6.0 t C ha^{-1} (Luo et al. 2006). It can be assumed that soil CO_2 efflux of *A. koreana* community is greater than alpine zone because they are distributed in sub-alpine zone. For instance, *A. holophylla* forests distributed in eastern Canada in regions with higher altitude than *A. koreana* community had lower soil CO_2 efflux of 3.5 t C ha^{-1} (Risk et al. 2002).

Relationship between soil respiration and precipitation

Figure 5 shows the regression analysis on monthly CO_2 efflux and precipitation of *Q. glauca* community and *A. koreana* community. The coefficient correlation (R) for monthly CO_2 efflux and precipitation of *Q. glauca* community and *A. koreana* community were 0.64 and 0.67 respectively which showed that precipitation had little effect on monthly CO_2 efflux. Nevertheless, the monthly change in CO_2 efflux in each community displayed similar patterns to the change in monthly precipitation in each study area (Fig. 5). It is known that soil respiration is affected highly by soil temperature and moisture (Davidson et al. 1998, Inclan et al. 2010).

Soil CO_2 efflux can mainly be attributed to respiration of root and heterotroph (Kuzyakov 2006, Saiz et al. 2006). Respiration of heterotrophs is dependent on soil moisture, and they proliferate in proportion to increase in soil water content (Darenova 2014). It has been reported that respiration of heterotrophs increase significantly straight after the rain and gradually subsides afterwards even though the lack of water content accumulated in soil acts as the limiting factor for soil respiration (Liu et al. 2002, Xu et al. 2004). Generally, soil respiration reaches its maximum point when the soil water content is neither too low nor high and optimum water content is known to be at 60% (Suh et al. 2009). In case of pastures on sub-alpine grassland, soil respiration increases as water content increases within the water content range of 10~80% (Moriyama et al. 2013).

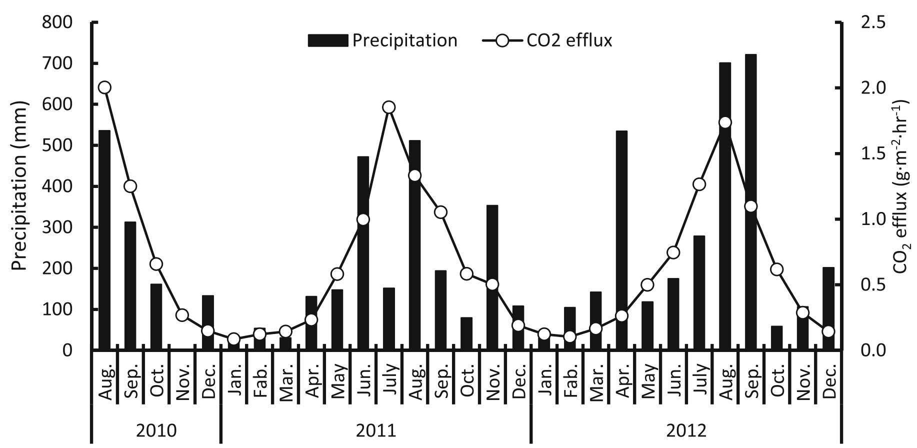
Table 3 Annual soil respiration (t CO_2 ha^{-1}) and organic carbon (t C ha^{-1}) of the *Q. glauca* and *A. koreana* communities

Community	2010 (Aug.~Dec.)		2011		2012	
	t CO_2 ha^{-1}	t C ha^{-1}	t CO_2 ha^{-1}	t C ha^{-1}	t CO_2 ha^{-1}	t C ha^{-1}
Q. glauca	31.9	8.7	56.4	15.4	51.9	14.1
A. koreana	19.7	5.4	35.3	9.6	33.1	9.0

The seasonal temperature change predominantly affected the monthly changes in soil CO_2 efflux shown in this study considering abovementioned characteristics of soil respiration with respect to soil temperature and water content. But it seems that variation in precipitation, a limiting factor in soil respiration, played a crucial role in soil respiration of *Q. glauca* community and *A. koreana* community.

Conclusions

This study analyzed the yearly and monthly variations of CO_2 efflux in relation to the soil temperature and precipitation in the *Q. glauca* community, a warm-temperate forest and the *A. koreana* community, a sub-alpine forest (CO_2 is emitted in forests as a result of CO_2 efflux. Although soil respiration is frequently used in research, CO_2 efflux was used in this study). The study results showed a high correlation between CO_2 efflux and either of soil temperature and precipitation. The average soil temperature was 7.5 °C higher in *Q. glauca* community than in *A. koreana* community at the depth of 10 cm below the ground surface. When the CO_2 efflux figures of two forest communities measured during the research were compared, the CO_2 efflux value of *Q. glauca* community was 1.6 times higher than that of *A. koreana* community, and this may be attributed to the temperature difference between the two communities due to the altitude



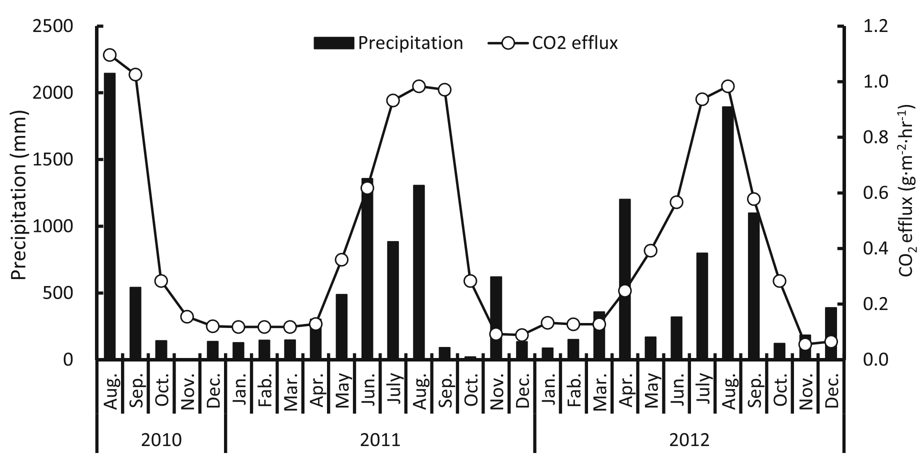


Fig. 5 The monthly variation of precipitation and modeled soil CO_2 efflux in the *Q. glauca* (above) and *A. koreana* (below) from in August 2010 to December 2012

difference. Furthermore, the monthly variation of CO_2 efflux exhibited a pattern similar to the monthly change of precipitation, and this fact may indicate that precipitation has an effect on the soil respiration of each community as a limiting factor. Soil respiration plays a vital role in the global carbon cycle regulation. Specifically, comprehensive and ongoing monitoring research on CO_2 efflux rates of forests and factors affecting them is required in order to estimate the change in the net ecosystem production (NEP) of forests caused by climate change and provide fundamental data for such analyses.

Abbreviations
NEP: Net ecosystem production; NPP: Net primary production

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

Competing interests
The authors declare that they have no competing interests.

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Ethics approval and consent to participate
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