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Experimental Throughfall Exclusion Studies on Forest Ecosystems: A Review

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Abstract

Climate change has been intensifying and affecting forest ecosystems. Over the years, the intensity and frequency of climate change have increased and the effects of climate change have been aggravating due to cumulative greenhouse gases such as CO_2, which has resulted in several negative consequences, drought being the main threat among all. Drought affects forest ecosystems directly and indirectly. Insufficient soil moisture, due to drought, may affect the growth of plants and soil respiration (SR), and soil temperature may increase because of desiccated soil. In addition, the mortality rate of plants and soil microorganisms increases. As a result, these effects could reduce forest productivity. Thus, in this article, we have presented various research studies on artificial drought using throughfall exclusion, and we have mainly focused on SR, which is significantly related to forest productivity. The research studies done worldwide were sorted as per the main groups of Köppen-Geiger climate classification and intensively reviewed, especially in tropical climates and temperate climates. We briefly reviewed the properties among the exclusion experiments about the temperate climate, which mostly includes Korean forests. Our review is not a proof of concept, but an assumption for adequate investigation of drought effects in the Korean forest.

Key Words: climate change, Köppen climate classification, throughfall exclusion, soil respiration, CO_2 efflux

Introduction

Climate change is apparent, and the terrestrial ecosystem in the last three decades has been much warmer than the decades since 1850. Climate change scenarios prognosticate increases in the global mean terrestrial temperature by maximum 8.5°C by the end of the 21st century. Moreover, extreme weather and climate events have been increasing in frequency and intensity since 1950. Especially, cumulative emissions of the greenhouse gas CO_2 is one of the key drivers of future climate events such as drought (Pachauri et al. 2014). Worldwide research studies related to changes in atmospheric CO_2 concentration have been rigorously conducted, and a more precise and accurate estimation of carbon dynamics in forest ecosystems is required (Dixon et al. 1994; Pachauri et al. 2014).

Forests and forest production are adequately controlled under suitable conditions, but climate change alters the natural integral part of forest ecosystems through disturbances both directly and indirectly (Dale et al. 2001; Lee 2019). Especially, temperature and precipitation are the most prominent limiting factors changing subsequent forest conditions. Changes in the global mean temperature and precipitation impact carbon dynamics in the forest ecosys-

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tem and alter forest processes and structures, because of which understanding the effects of climatic changes on the forest ecosystem is particularly important (Boisvenue and Running 2006; Allen et al. 2010).

All other terrestrial-atmospheric carbon exchanges are surpassed by CO_2 emissions from soils such as soil respiration (SR) except for gross photosynthesis (Raich and Schlesinger 1992). SR is carbon dioxide emission from soils driven by roots and soil organisms (Raich and Schlesinger 1992). It has been reported that almost 10% of the atmospheric CO_2 passes through soils annually (Raich and Potter 1995). Thus, it is important to examine correlations among climatic factors, vegetation distributions, and SR rates (Raich and Schlesinger 1992; Raich and Tufekcioglu 2000; Schlesinger and Andrews 2000).

Manipulative experiments to study greenhouse gas efflux from forests have been globally conducted involving various scales of water exclusion experiments (Yahdjian and Sala 2002). In Germany, van Straaten et al. (2011) examined differences in soil CO_2 efflux and soil moisture responded to artificial drought conditions in Indonesia. They reported a significant reduction of soil CO_2 efflux under the experimental drought. In addition, in Spain, Casals et al. (2011) evaluated differences in soil CO_2 efflux through the severe drought conditions in the Mediterranean Quercus forest.

Changes in forest ecosystem diversity, terrestrial carbon sink, and the global carbon cycle in response to climate change are affected by increasing temperature, CO_2 concentration, and nitrogen deposition, and these responses are different depending on the regional climatic and environmental conditions (Grace et al. 2002). Besides, SR differs with vegetation; hence, vegetation type is a vital determinant of SR rate (Schlesinger 1977; Singh and Gupta 1977; Raich and Schlesinger 1992; Raich and Tufekcioglu 2000). Therefore, it is inappropriate that results on throughfall exclusion experiments conducted from various research regions applied for CO_2 effluxes study under drought conditions in the Korean forest ecosystem; moreover, these studies cannot be applied to handle future drought events. Hence, we reviewed trends and results of international experimental throughfall exclusion studies that may be suitable direction for future research. In addition, we briefly reviewed the properties among the exclusion experiments about the temperate climate, which mostly includes Korean forests. Our review is not a proof of concept, but an assumption for adequate investigation of drought effects in the Korean forest.

Research on throughfall exclusion experiments

Changes in patterns of air temperature and precipitation driven by climate change affect the large pool of carbon held in forest soil (Sowerby et al. 2010). The relation between climate change and forest ecosystems, carbon loss from soil, soil composition, structure of forests, and disturbances are the main issues in forest environmental science (Dale et al. 2000; Grace et al. 2002; Allen et al. 2010; Sowerby et al. 2010). The global terrestrial carbon cycle and tree lines have implications in response to environmental change (Grace et al. 2002). Increasing temperature, atmospheric CO_2 concentration, and nitrogen deposition interactively co-vary and alter forest climate (Grace et al. 2002; Allen et al. 2010).

Because the growth and reproduction of trees depend on environmental factors, understanding the relationship between tree growth and climate to manage future forest resources (Seo and Park 2010). Thus, it is difficult to directly apply the results that have been reported worldwide to the new throughfall exclusion experiments in different climate environment. Therefore, we sorted worldwide research studies on throughfall exclusion experiments into main climate groups of Köppen-Geiger climate classification and reviewed them.

Throughfall exclusion experiments by main climate groups of Köppen-Geiger climate classification

Worldwide research studies used various extents of throughfall exclusion. The effects of drought stress on forest soil carbon cycle (Davidson et al. 2004; Borken et al. 2006a; Asensio et al. 2007; Davidson et al. 2008; Cleveland et al. 2010; Sowerby et al. 2010; van Straaten et al. 2011; Kim et al. 2018), vegetation mortality, phonology, the fine root systems of mature plant (Gaul et al. 2008), above-ground production of plants, and biomass storage have been examined (Nepstad et al. 2002; Ogaya et al. 2003; Da Costa et al. 2010; Moser et al. 2014).

However, the mean temperature and precipitation differ with region, and variation of growth conditions of the forest by climate zone is an affected influence on the results of the study; thus, we sorted the current study results into main climate groups of Köppen-Geiger climate classification including tropical climates, temperate climates, continental climates, and alpine climates.

As the purpose of this is eventually to provide an adequate direction of drought effects in a temperate climate, especially in Korea, and, for the reasons mentioned above, all other terrestrial-atmospheric carbon exchanges are surpassed by CO_2 emissions from soils such as SR with the exception of gross photosynthesis (Raich and Schlesinger 1992), also it was reported that almost 10 % of the atmos-

Table 1. Experimental throughfall exclusion on tropical climates

Study location	Study period	Annual average temperature (°C)	Annual average precipitation (mm)	Altitude (m)	Forest type	Soil classification	Plot design	Reference
Brazil's Tapajós national forest, in east-central amazonia	Dec. 1998-Apr. 2001	26	2000 (600-3000)	200	Amazonia tropical rainforest	Oxisol	Drought and control plot on 100×100 m (used 3×0.5 m panel)	Nepstad et al. 2002
Tapajós national forest, in east-central amazonia	Sep. 1998-Dec. 2002	28	2000 (600-3000) most of rainfalls during Jan.-June	200	Mature evergreen forest	Oxisol	Drought and control plot on 100×100 m (used 3× 0.5 m panel)	Davidson et al. 2004
Tapajós national forest, pará, brazil	Aug. 1999-Dec. 2004	28	2000 (1700-3000), 10 mm with dry season (July to Dec.)	200	Amazonia tropical rainforest	Haplustox	Drought and control plot on 100×100 m (used 3× 0.5 m panel)	Brando et al. 2006
The Tapajós (TNF) and Caxiuanã (CAX) national forests, Pará, brazil	TNF: 1999-2006 CAX: 2001-2008	TNF: 26 (21-31) CAX: 26	TNF: 2000 CAX: 2272	TNF: 190 CAX: 30	Amazonia tropical rainforest	Oxisol	Drought plots on 0.8×1.8 m	Powell et al. 2013
Caxiuã national forest, Para, brazil	Dec. 2001-Nov. 2002, Dec. 2002-Nov. 2003	26	2,272 (555 mm on dry season)	50	Lowland rainforest	Yellow Oxisol	Drought plots on 0.8×1.8 m	Sotta et al. 2007
Central Sulawesi, indonesia	Jan. 2006-Dec. 2006	21.3	2,672	1,050	Pre-montane tropical rainforest	Nitisols	Drought and control plots on 40 m×40 m	Moser et al. 2014
Central Sulawesi, indonesia	May 2007-Sep 2009	20.6	2,901	1,050	Sub-montan e tropical forest	Nitisol	Drought and control plots on 40 m×40 m	van Straaten et al. 2010
Osa peninsula in the Golfo Dulce forest reserve, southwest Costa Rica	Nov. 2007-Nov. 2008	26.5	>5000 (<100 per month when dry season between Dec.-Apr.)	150	Lowland tropical rainforest	Ultisol	Droughts plots on 2.4× 2.4 m	Cleveland et al. 2010

pheric CO_2 passes through soils annually (Raich and Potter 1995). Therefore, among various experiments, we selected research studies on throughfall exclusion experiments, excluding precipitation experiments in arid climates, and reviewed research studies on the CO_2 emissions driven by the soil from among these throughfall exclusion experiments.

Tropical (megathermal) climates

The Amazon tropical rainforest has 70-120 Pg of carbon in its vegetation (Houghton et al. 2001; Malhi et al. 2006; Saatchi et al. 2007; Da Costa et al. 2010), which significantly impacts the global carbon cycle (Malhi et al. 2006; Cleveland et al. 2010). There has been a prediction by at least one climate model that there will be severe reduction in precipitation in the tropical region in this century. Following these predictions, throughfall exclusion experiments have been carried out to study the effects of droughts on tropical rainforest (Nepstad et al. 2002; Davidson et al. 2004; Brando et al. 2006; Davidson et al. 2008; Cleveland et al. 2010; Da Costa et al. 2010) (Table 1). The experiments were mostly conducted on plots, each measuring 10 ha, and which were extensive compared to other climate regions, which ranged between 20 m^2 and 1,600 m^2. The slope of the Amazonia rainforest region is mostly flat; hence it was possible to conduct extensive research. However, several studies were conducted on smaller and differing drought conditions (Cleveland et al. 2010). Cleveland et al. (2010) measured the effect of experimental drought on SR rate using 2.4×2.4 m plots. They conducted the variation of drought treatment (-50%, -25% of throughfall exclusion) and ten replicates per treatment in the lowland tropical rainforest in Southwest Costa Rica. They suggested the possibility of increasing insoluble carbon concentrations during drought conditions, because relatively wet rainforest regions contributed to rapid respiration of both incoming and existing soil organic carbons. These results showed that future drought as a result of climate change could hasten soil carbon loss in tropical rainforests and change the forest ecosystem.

Brando et al. (2008) estimated the effect of the throughfall exclusion treatment on soil CO_2 efflux using a 1 ha plot and a similar control plot. They adjusted effective rainfall, which was reduced by approximately 35-41%, using the panel in Tapajós National Forest, Brazil. Their results suggested that the effects of treatment on soil CO_2 efflux were not consistent with years or seasons. There was only a significant treatment by year interaction. They considered this because new root growth occurs at deeper soil layers during drought conditions and these roots may have frustrated with the lack of available moisture on the soil surface. These probable responses may support to account for the lack of a constant and important treatment effect on soil CO_2 efflux.

Van Straaten et al. (2011) estimated the effects of drought on soil CO_2 efflux and CO_2 production sources using three plots measuring 40×40 m and compared them with three control plots in the sub-montane forest in Indonesia. The study periods comprised variation of throughfall exclusion that was 2.5 months of pre-treatment, 9 months of 50% exclusion, 15.5 months of 80% exclusion, and the last 4 months of opening the roof. They reported that soil CO_2 efflux significantly decreased during drought, which also decreased in the control plots (23% in the first 9 months and 48% in the last 15.5 months), because each plot was affected by both autotrophic and heterotrophic SR sources. Hence, their result showed that this forest ecosystem is responsive to drought.

Moser et al. (2014) examined rising drought risk in South-East Asia using 40×40 m throughfall exclusion panels. They conducted the study by varying drought conditions (60% of throughfall reduction (TFR) in the first 8 months and 80% of TFR in the following 17 months) and three replicates per treatment in a prehumid tropical climate in Sulawesi, Indonesia. They reported that the mortality rate did not increase under drought conditions, and during severe drought conditions, the average wood production reduced by 40%. In addition, leaf litterfall was not sensitive to experimental desiccated soil, and only during a few sampling dates, the litter masses were significantly reduced on the roofs. After artificial droughts, fine root biomass reduced by 35%, but fine root necromasses increased by 250%; this implies fine root mortality elevation by desiccated soil conditions. This study examined the effects of drought under prehumid tropical climates. However, natural droughts exert more rapid stress during a relatively short period than artificial droughts, that is, because of the higher relative humidity of experiment plots than that in the natural dry season, differences between the result and the observed natural references occurred. These results showed the necessity of manipulation, that is, the quite exclusion of throughfall and soil desiccation rate as well as a relatively moist atmosphere that affected the soil in throughfall exclusion experiments.

Although many studies were conducted under inappropriate conditions, Powell et al. (2013) evaluated measurements from two large-scale Amazon drought experiments using five models. Model predictions corresponded with the observed carbon fluxes in the controls of each experiment, but the replicates of responses to the drought treatment were insufficient. Besides, respective models had unsatisfactory conditions, both dynamic and hydrodynamic vegetation.

Temperate (mesothermal) climates

Many artificial drought experiments conducted in temperate climates included the Mediterranean basin, Spain (Ogaya and Peñuelas 2004; Asensio et al. 2007; Sowerby et al. 2010) (Table 2). Asensio et al. (2007) examined the effects of the future drought condition on soil CO_2, monoterpenes, and other volatile organic compounds exchange rates and their seasonal and interannual variations. Twenty-four throughfall exclusion plots (1×10 m) were constructed on a relatively short natural holm oak forest (3-4 m tall) in the Prades Mountain, in Southern Catalonia. They divided study periods from April 2003 to April 2004 and from November 2004 to July 2005. Drought treatment significantly reduced SR during the wet year, particularly, in both springs in the first year. Although SR on drought conditions was reduced until spring 2005, the effect of the drought conditions almost did not affect SR. Seasonal soil CO_2 efflux variations significantly followed soil moisture variations all over the sampling periods; on the contrary, the relationship between SR and soil temperature was not linear. In addition, this study showed the characteristics of the drought-stressed regions, that is, during the wet year, the SR rate recorded maximum CO_2 efflux in springs and autumn, and minimum efflux was recorded in the summer drought.

On the contrary, Lu et al. (2017) examined the effects of

Table 2. Experimental throughfall exclusion on temperate climates

Study location	Study period	Annual average temperature (°C)	Annual average precipitation (mm)	Altitude (m)	Forest type	Soil classification	Plot design	Reference
German solling research area	1993 Apr.-Sept., 1994 Apr.-July (drought) 1993 Sept.-Oct., 1994 July-Aug. (rewetting)	6.4	1,090	350	118-yr-old norway spruce plantation	Typic dystrochrept	Drought and rewetting plot, drought only plot, and ambient plot (without roofs) on 300 m^2 roofs	Borken et al. 1999
NE Wales, UK	June 1999 - Oct 2006	8.2	1,323	-	Scrublands	Humo-frric podzol	Drought and control plots on 4 m×5 m	Sowerby et al. 2010
Harvard forest in Petersham, Massachusetts	June 2001-Nov. 2003	8.5	1,050	340	Mixed deciduous forest	Well-drained typic dystrochrept	Drought plots on 5×5 m	Borken et al. 2006b
Southern Catalonia, Spain	Apr. 2003-July 2005	12	658	930	Holm oak forest	Xerochrept	Drought and control plots on 15 m×10 m	Asensio et al. 2007
The Baotianman natural reserve, central China	2013-2016 (growing seasons)	15.1	890	1,400	Warm-temperate oak forest	Haplic luvisol	Drought plots on 20×20 m	Lu et al. 2017

reduced rainfall on total SR, heterotrophic SR (HR), autotrophic SR (AR), soil microbial biomass, and fine root biomass in a warm-temperate oak forest in central China. They constructed three 20×20 m plots to exclude approximately 50% TFR during the growing seasons from 2013 to 2016. The 0.7 m deep trenches around the plot were used to prevent both the potential lateral water and surface run-off by using plastic plates. The SR, HR, and AR nearly followed the seasonal trend of the soil temperature at 0-5 cm depth in both plots. The temperature on SR and HR was positively correlated with the soil moisture at 0-5 cm depth, while on AR, the temperature was not correlated with the soil moisture. Different from their hypothesis, HR and microbial biomass consistently were not affected by TFR. In addition, TFR did not generally affect the annual cumulative SR, HR, and AR, although TFR had significantly reduced soil moisture in the topsoil, soil CO_2 efflux, microbial biomass, and fine rootstocks were scarcely affected. Roofs desiccated soil, but the tree crowns higher than roofs and atmospheric conditions such as vapor pressure were almost unaffected by the exclusion. As a result, because perfect exclusions were unenforceable in TFR, understanding of the natural soil carbon cycling under the TFR could be contradicting. Thus, the best prediction on the ecosystem response to TFR would have progressed in the first study year, which was under natural drought conditions.

Borken et al. (2006b) examined the effects of an experimental summer drought on SR and radiocarbon efflux using throughfall exclusion (TFR). They constructed studies on 5×5 m throughfall exclusion plots, while nearby control plots directly received throughfall in a mixed deciduous forest in the Harvard Forest, in Massachusetts, USA. The treatments were replicated three times and conducted from 2001 to 2002, only during summers. The experiment showed that the extended summer drought decreases SR, and the differences in moisture availability between treatment and control plots indicated that the SR was mainly affected by TFR, especially in the O horizon. These results reported that interannual variability in climate might influence the soil source, as the variability can similarly affect the interannual variation in net ecosystem exchange. Although this study period was not enough to anticipate the effects of long-term climate change, these effects potentially influence the long-term patterns of Net Primary Productivity, carbon allocation, and carbon inputs to soils.

Continental (microthermal) climates and alpine (montane) climates

Climate change have been predicted to alter rainfall patterns such as by possibly reducing precipitation in the growing season. These changes possibly affect the ecosystem properties including that of soil and vegetation, and thus, finally alter productivity and biodiversity (Kim and Choi 2018). Yun et al. (2014) examined the effect of warming treatment and altering precipitation based on a climate change scenario in Korea. They constructed 1.5×1.5 m treatment plots and subjected them to temperature increases of 3°C and reduced precipitation by 30% to imitate future climate conditions in Korea. The variations in rainfall manipulation were three types that comprised -30%, +30%, and 0% of precipitation. The study was conducted in 2-year-old coniferous forests from May to November 2013. Their findings showed that the average air temperature was significantly different between treatment and control plots. The average air temperature was higher in the warm plots, and the highest temperature was recorded in the lowest precipitation plots. Besides, the mean soil temperature significantly differed among the treatments, and soil temperature in the warm plots was higher than that in control plots. In addition, the average soil moisture content substantially different among treatments. After 2 years, Yun et al. (2014) reported the effect of warming treatment and altering precipitation on the growth, photosynthetic rate, and chlorophyll content of *Pinus densiflora* seedlings under the same research conditions. In this study, although the effect of treatment on the height and growth was unclear, net photosynthetic rate and total chlorophyll which are significantly changed content had the potential to alter further ecophysiological responses in the seedlings. Because the treatments were highly correlated with soil moisture and both air and soil temperature, respectively, after the year following this study, a difference in the height and growth is expected in the treatment plots. Because this result was acquired in an open-field experiment, it is difficult to conduct in the natural forest ecosystem. Therefore, the following studies need to closely simulate the natural forest ecosystem and the future drought conditions.

On the contrary, Fay et al. (2000) investigated the effects

Table 3. Experimental throughfall exclusion on continental and alpine climates

Study location	Study period	Annual average temperature (°C)	Annual average precipitation (mm)	Altitude (m)	Forest type	Soil classification	Plot design	Reference
Northeastern Kansas, Konza Prairie	1998 June-Oct.	12.0	835 (almost rainfalls during the growing season, May-Sep.)	343	Mesic tallgrass prairie	Irwin silty clay loams	Drought plots (30% excluded) on 9×14 m and interrainfall periods (50% increased) on 6×6 m plot	Fay et al. 2000
Austrian central alps near Neustift, Stubai Valley	2010 June-Aug.	3.0	1,097	1,850	Mountain meadow	Dystric cambisols	Drought plots on 3.0×3.5m	Fuchslueger et al. 2014a

of altering rainfall on vegetation species composition, nutrient cycling, and plant growth dynamics aboveground and belowground (Table 3). They manipulated rainfall timing and quantity in a mesic grassland using exclusion panels. Twelve 9×14 m rainfall exclusion panels were constructed to examine the effects of 30% reduced rainfall quantity and 50% increased interval of dry periods. Increased intervals of dry periods reduced aboveground net primary productivity, soil CO_2 flux, and flowering duration, but reduced rainfall quantity generally did not affect these factors. Consequently, this study showed that altered rainfall patterns affected by climate changes may regulate the responses such as microbial activity, biomass accumulation, plant life histories, and other ecological properties that were related to the interval of rainfall and temporal patterns of soil moisture.

In addition, other researchers constructed experimental drought plots, but they investigated the effects of throughfall exclusion on xylogenesis of balsam fir (D'Orangeville et al. 2013). To summarize, the treatment significantly reduced soil moisture content, and, tracheids were smaller in experimental trees than in control trees, and the seedlings displayed growth reduction. Their results indicated that the future severe drought conditions may exert negative effects on the duration of xylogenesis and the production of xylem cells in balsam fir.

In alpine climates, it is not about SR or CO_2 efflux, but some studies were conducted. Fuchslueger et al. (2014a, 2014b) examined the transfer of fixed plant carbon to soil microbes and alteration of the bacterial community composition under artificial drought conditions in the Austrian Central Alps near Neustift, Stubai Valley. They constructed three 3×3.5 m rainfall exclusion plots on a meadow to simulate summer drought from June to August 2010. Their findings showed that microbial biomass was higher in artificial drought plots. The treatment changed the microbial community composition in the favor of gram-positive bacteria. The drought conditions, however, did not explain the transfer of plant carbon to fungi, but when the meadow was cropped, the researchers observed that uptake from the bacterial consortia was diminished. Consequently, the result suggested that the carbon connection between plant and soil microbes may have weakened by drought, and the microbial consortia within study plots were found to be adapted for soil moisture conditions, such as slow growing (i.e., gram-positive bacteria), under drought conditions and recovered quickly after rewetting.

Conclusion

Research studies on differences in soil CO_2 efflux have been conducted using throughfall exclusion experiments in forests. We sorted these research studies into main climate groups of Köppen-Geiger climate classification to better understand relation between CO_2 efflux and drought effects.

Large-scale experiments have been conducted on throughfall exclusion in tropical climate regions, but the margin of error has been high because of large number of variables, which was of the large scale of the experiments. On the contrary, studies that were conducted on a relatively smaller scale in the temperate climates zones required more investigation. This is because, overall, the factors affecting the difference in soil CO_2 efflux by throughfall exclusion experiments were mostly temperature and moisture; however, depending on the region of the experiment, only temperature or moisture had significant effect. The experimental design of throughfall exclusion is important to exclude throughfall precipitation using panels as well as to exclude surface runoff using trench in the soil, because moisture affects plant roots and soil microbial respiration. In particular, it is more necessary to exclude surface runoff in terrain where most forests, such as Korea, are located on slopes. Several studies have been conducted in tropical climate regions, which were higher than those conducted in temperate climate regions.

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