[Turkish Journal of Agriculture and Forestry](https://journals.tubitak.gov.tr/agriculture)

Volume 47 | Number 1 Article 13

1-1-2023

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Recommended Citation

KIM, GWANG JUNG; JO, HEEJAE; KIM, HYEONJI; CHO, MIN SEOK; NOH, NAM-JIN; CHANG, HANNA; KIM, HYUNG-SUB; and SON, YOWHAN (2023) "Experimental design of open-field temperature and precipitation manipulation system to simulate summer extreme climate events for plants and soils," *Turkish Journal of Agriculture and Forestry*: Vol. 47: No. 1, Article 13. https://doi.org/10.55730/1300-011X.3070
Available at: https://journals.tubitak.gov.tr/agriculture/vol47/iss1/13

Turkish Journal of Agriculture and Forestry

http://journals.tubitak.gov.tr/agriculture/

Research Article

Turk J Agric For
(2023) 47: 132-142
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doi:10.55730/1300-011X.3070

Experimental design of open-field temperature and precipitation manipulation system to simulate summer extreme climate events for plants and soils

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Received: 01.03.2022 • **Accepted/Published Online:** 16.08.2022 • **Final Version:** 08.02.2023

Abstract: Extreme climate events are expected to occur very frequently and intensively with climate change, and such extreme events can induce irreversible damage to plants and soils, as well as ecosystems. Accordingly, there is a need to understand the effects of extreme climate events on ecosystems. Here, we designed a temperature and precipitation manipulation system to simulate extreme climate events of heat, drought, and heavy rainfall. We constructed three soil surface temperature manipulation levels (control, 3 °C, and 6 °C increases) and three precipitation manipulation levels (control, drought, and heavy rainfall) with six replicates, and operated these from day of year (DOY) 195 to 233 in 2020. Infrared heaters increased the soil surface temperature during the extreme heat treatments. For precipitation manipulation, the automatic rainout shelter excluded ambient rainfall to produce drought conditions and an artificial rainfall simulator with spray nozzles produced heavy rainfall conditions. As a result, the soil surface temperature (°C ± one standard deviation) was higher in the 3 °C and 6 °C heated treatments than in the control by 2.7 ± 0.2 and 5.7 ± 0.5, respectively. The mean soil water content (vol. %) was 12.9 ± 8.6 in the drought treatment, 14.1 ± 7.8 in the control, and 16.1 ± 8.3 in the heavy rainfall treatment during the precipitation manipulation period. The results showed that the system design and operation were as expected. The designed system can be effectively utilized to investigate the responses of plants and soils to extreme climate events.

Key words: Extreme climate events, climate change, multifactor experiment, system design, ecosystems

1. Introduction

Climate change induces not only the rise in global surface air temperature and changes in the amount of precipitation, but also the frequency, duration, and intensity of extreme climate events (National Academies of Science, Engineering, and Medicine, 2016). For instance, the number of days with daily maximum temperatures above the 90th percentile increased globally in the 2000s compared to that in the 1950s (Alexander et al., 2006). Heat extremes may occur annually in most European countries, and they would last for 3 months in tropical regions over the twenty-first century if the air temperature increased by 2 °C in comparison to that of preindustrial levels (Schleussner et al., 2016; King and Karoly, 2017). Likewise, the maximum duration of extreme drought could be longer in 2070–2100 by approximately 2 months than that in 1960–2020 under the representative concentration pathway (RCP) 8.5 (Lin et al., 2020). The number of days with heavy rainfall has been rising since 1950, increasing by 2 days per decade in some regions of the United States and South America (Alexander et al., 2006). The intensity of heavy rainfall would also increase by 5%–7% in the late twenty-first century compared to that in 1986–2005 (Schleussner et al., 2016).

Frequent, enduring, and intense extreme climate events affect ecosystems, especially plants and soils. Most plants are resilient to heat and water stresses, however, extreme conditions delay recovery mechanisms and lead to irreversible damage (Ruehr et al., 2019). Extreme heat degrades photosynthetic activity, chlorophyll functions, and biomass growth of woody plants (Ameye et al., 2012; Bauweraerts et al., 2013). Additionally, extreme heat limits soil enzymatic activities, especially in cambisols (Hansen et al., 2018). Extreme drought diminishes the cover of annual forbs and grasses in both infertile and fertile soils (Copeland et al., 2016). Enzymatic activities in grassland

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soil decrease under extremely dry soil conditions during spring and summer (Hammerl et al., 2019). Heavy rainfall might increase the mortality of grassland species by inducing interspecific competition (Grant et al., 2014). In particular, summer extreme climate events have an extremely significant impact on ecosystems. The summer extreme temperatures and droughts in 2003, 2010, and 2018 in western Europe severely reduced total ecosystem respiration, net ecosystem production, and gross primary production (Bastos et al., 2020). The amount of rainfall in summer affects water use efficiency in some Crassulacean acid metabolism (CAM) and herbaceous plants because they entirely use moisture from summer rain (Ehleringer et al., 1999). Schwinning et al. (2005) reported that summer drought could reduce photosynthesis in perennial species. In addition, the unusual warm, wet, and dry spells have been frequently observed in Asian monsoon climate region such as South Korea, Japan, and China in summer (World Meteorological Organization, 2021). The summer extreme drought with extreme hot conditions in 2003 significantly decreased the gross primary productivity (GPP) of forest ecosystems in East Asia (Saigusa et al., 2010). Shan et al. (2021) who studied the correlation between extreme climate events and tree-ring chronology in China showed that extreme temperature and precipitation might lead to the outbreak of pest diseases and degrade the *Malus sieversii* forests.

Creating artificial extreme conditions for ecosystems is an ideal method to investigate their responses to extreme climate events. The experiment of environmental factor manipulation allows researchers to precisely determine the mechanisms between environmental factors and ecosystems (Rustad, 2006). Many attempts have been made to design a temperature or precipitation manipulation system. Infrared heating systems have been widely used to warm tropical understories, temperate coniferous and deciduous species, and subalpine trees (Moyes et al., 2013; Noh et al., 2017; Kimball et al., 2018; Chang et al., 2020). Misson et al. (2011) simulated drought in woody plants using a mobile rainfall shelter, and Kavian et al. (2019) devised a rainfall simulator to study the effects of acid rain on soil erosion. However, only a few studies have dealt with extreme climate events compared to research on the effects of changes in mean climatic values (Jentsch et al., 2007). Moreover, most previous studies have treated isolated climatic conditions. This is because simulating two or more factors requires larger experimental sites, more complicated techniques, and higher costs than applying a single factor (Beier et al., 2012). Nonetheless, it is necessary to investigate the relationships between multiple extreme events and ecosystems because concurrent extreme events have highly significant effects on ecosystems (Allen et al., 2015; Beillouin et al., 2020). Furthermore, a multifactorial approach can play a significant role in understanding nonlinear interactions among individual climatic factors (Mikkelsen et al., 2008). The more realistic models on the responses of ecosystems to the climate change can be developed utilizing these findings.

We constructed an open-field temperature and precipitation manipulation system to simulate three extreme climate events of heat, drought, and heavy rainfall and their combinations for small-sized plants such as seedlings or herbaceous species and soils. The objective of this study was to design an appropriate manipulation system, and to verify and discuss the functionality of the designed system.

2. Materials and methods

2.1. Setting extreme climate events scenarios

We used meteorological data for the experimental month (July–August) during the 59-year period (1961–2019) in Seoul as the reference period (Korea Meteorological Administration, 2020). Extreme heat was defined as the 90th and 99th percentiles of the daily maximum temperature (TX90p and TX99p) during the reference period (Alexander et al., 2006). We calculated the difference between the extreme heat and the mean daily maximum temperature during the reference period to set the target temperature. The duration of extreme heat treatment was considered as the longest consecutive day with a daily maximum temperature higher than the threshold of extreme heat. The mean daily maximum temperature was 29.9 °C, whereas the thresholds of TX90p and TX99p were 33.2 °C and 36.0 °C, respectively. We increased the soil surface temperature in the heated plots by 3 °C and 6 °C for 7 days compared to that in the control.

For extreme drought, we analyzed the longest consecutive days with rainfall of less than 1 mm during the reference period (Grant et al., 2014). Consequently, we excluded ambient rainfall for 9 days to simulate extreme drought. Heavy rainfall was considered to be the 95th percentile of daily precipitation (R95p; Zakaria et al., 2017; Pendergrass, 2018). We determined the longest consecutive days with daily precipitation more than the threshold of heavy rainfall for the treatment duration. Accordingly, stored water corresponding to a rainfall of 113 mm day^{-1} was irrigated every 3 days during the drought treatment period.

2.2. Experimental design

The experiment was conducted at an open-field nursery in Forest Technology and Management Research Center, Pocheon, South Korea (37° 45′ 38.9″ N, 127° 10′ 13.4″ E). The mean annual air temperature and precipitation over 23 years (1997–2019) were 10.2 °C and 1364.9 mm, respectively, at this site (Korea Meteorological Administration, 2020). The soil texture in the plots was sandy loam (70% sand, 20% silt, and 10% clay), and soil pH and cation exchange capacity (CEC) were 6.42 and 6.78 cmolc kg^{-1}, respectively. In April 2020, we constructed 54 plots with a dimension of 1.5 m × 1.0 m and arranged each plot with a 0.5 m upward and 1.5 m sideward spacing to prevent treatments from affecting each other. We combined three temperature manipulation levels [temperature control (TC), TX90p condition (T90), and TX99p condition (T99)] and three precipitation manipulation levels [precipitation control (C), drought (DR), and heavy rainfall (HR)] with six replicates for each treatment (Figure 1). In addition, a rubber packing (5 m long and 0.4 m wide) surrounded each plot for 0.1 m above and 0.3 m beneath the soil surface to avoid the flow of water between the plots.

We manipulated the temperature and precipitation from July 13 to August 20, 2020 (Figure 2). We treated the first precipitation manipulation, excluding the rainfall in DR plots from July 13 to 21 [day of the year (DOY) 195–203] and irrigated HR plots on July 15, 18, and 21 (DOY 197, 200, and 203, respectively). Then, the first temperature manipulation was performed from July 22 to 28 (DOY 204–210). The rest period was from July 29 to August 4 (DOY 211–217). The second drought period for DR plots was from August 5 to 13 (DOY 218–226), including the second heavy rainfall treatment for HR plots on August 7, 10, and 13 (DOY 220, 223, and 226, respectively). We also treated the second temperature manipulation from August 14 to 20 (DOY 227–233).

2.3. Equipment

We used infrared heaters (FT-1000, Mor Electronic Heating Assoc., Comstock Park, MI, USA) for the extreme heat treatment. An infrared heating system can provide a realistic heating mechanism (Harte et al., 1995), and is a cost-effective method (Kimball et al., 2008). Infrared heaters were installed 90 cm above the soil surface, and the gap between the heaters was 20 cm. An infrared thermometer (SI-111, Apogee Instruments, Logan, UT, USA) was used to measure the soil surface temperature. Infrared heater and thermometer were bolted to the steel pipe. Data loggers (CR1000X, Campbell Scientific, Inc., Logan, UT, USA) and relays (SDM-CD-16AC, Campbell Scientific, Inc., Logan, UT, USA) maintained the targeted soil surface temperatures in T90 and T99. For example, if the soil surface temperature in T90 and T99 reached the target temperature, the relays switched off the heaters. In contrast, the relays switched on the heaters if the temperature fell below the target temperature. We used two and three infrared heaters in T90 and T99, respectively. Dummies of infrared heaters were installed in TC and T90 to ensure that every plot had an equal light environment by inducing equivalent shadows within the plots.

The effect of shelters on environmental factors (e.g., light, temperature, and air) should be considered when simulating drought using shelters (Beier et al., 2012). In contrast to the permanent shelter, the automatic shelter has advantages in that it does not induce passive warming

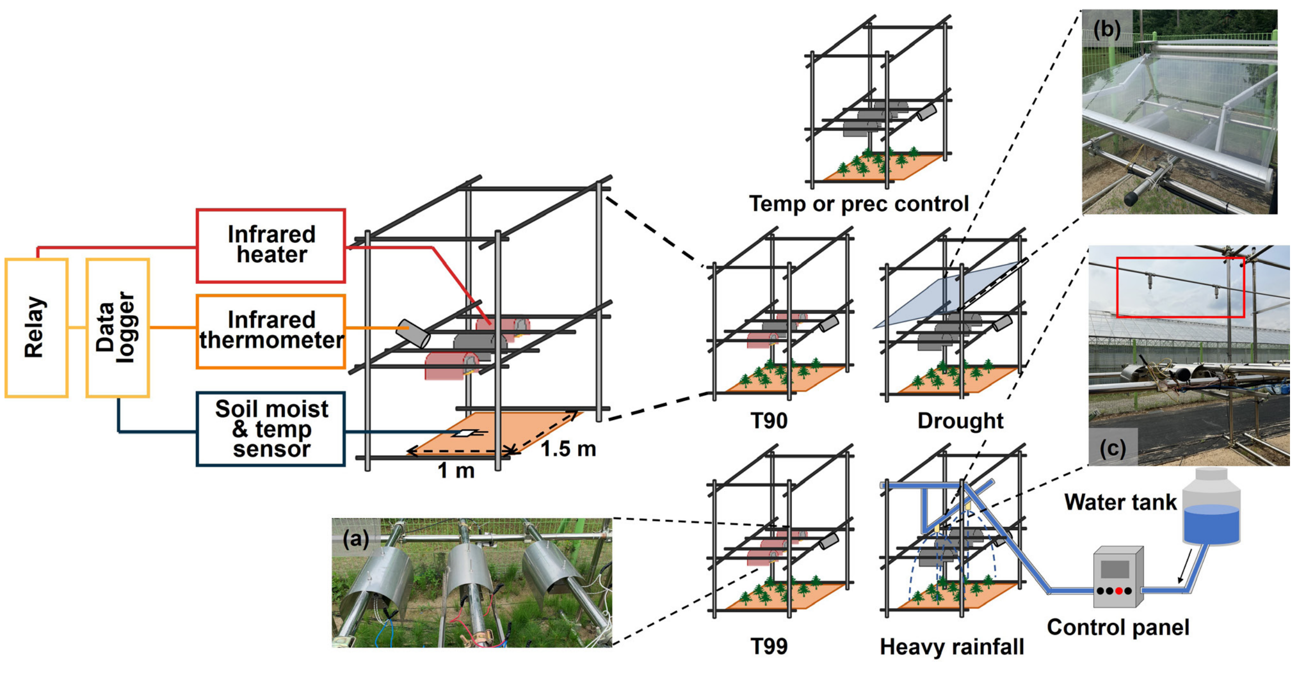

Figure 1. Description of temperature (temp) and precipitation (prec) manipulation system. (a), (b), and (c) are scene photos of infrared heaters, rainout shelter, and spraying nozzles (in red-lined square), respectively. T90 and T99 indicate that treatments simulating the 90th (TX90p) and 99th (TX99p) percentiles of daily maximum temperature during the reference period, respectively.

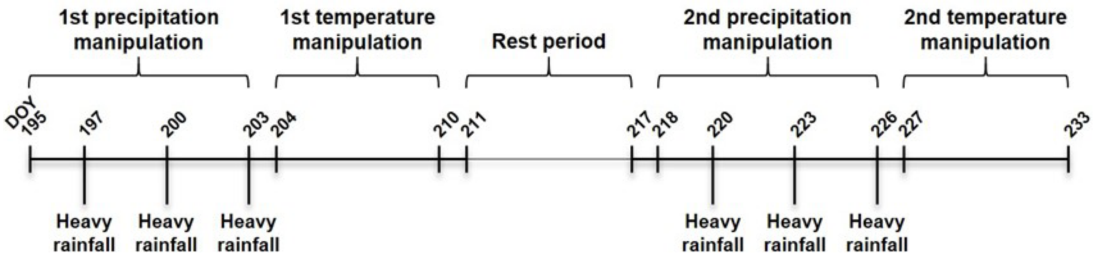

Figure 2. Experimental scheme of the current study. DOY means day of the year.

and wind stress within the plots. The rainout shelter, which has an opaque roof, can affect plants by intercepting light. Therefore, we adopted an automatic rainout shelter with a roof using a transparent thermoplastic polyurethane sheet. The rainout shelter (2.0 m × 1.5 m) was hooked to a rain detector (HTL-301, Haimil, Korea), and excluded any ambient rainfall in DR at a height of 1.6 m from the soil surface. The shelter closed only when detecting rainfall to avoid a disturbance of light absorption by plants and to allow air to flow through the plots. The shelter provided an inclination to exclude rainfall and water flow from the plots.

Two spraying nozzles (Unijet D5-35, Spraying Systems Co., Wheaton, IL, USA) per plot were used in the rainfall simulator. The rainfall simulator sprayed water from a height of 1.6 m above the ground to create more realistic rainfall conditions than that with irrigation at ground level (Chang et al., 2020). The spraying time and pressure were set through a control panel. We considered the drop size to be similar to the natural drop because the drop size is a very important aspect when mimicking rainfall (Blanquies et al., 2003). The drop size of natural rainfall has a wide distribution ranging from roughly 0 mm to 7 mm (Fernández-Gálvez et al., 2008), and the common distribution of drop diameter in South Korea ranges from 0.5 mm to 0.8 mm (Korea Meteorological Administration Weather Radar Center, 2014). Therefore, we selected a drop size of 0.7 mm, considering both the technical characteristics of the nozzle and the range of the natural drop diameter. We applied 170 L day^{-1} (121 L h^{-1} for 1.4 h) of stored water at a pressure of 1.0 bar to each HR plot.

Single soil moisture and temperature sensor (CS655, Campbell Scientific, Inc., Logan, UT, USA) per plot was used to measure the soil water content and soil temperature at a depth of 5 cm at the center of the plots. Data loggers recorded the soil surface temperature at 1 min intervals, and soil temperature and soil water content every 30 min. An automatic weather station recorded the hourly precipitation.

2.4. Statistical analysis

We calculated the daily mean soil surface temperature, soil temperature, and soil water content using these 30 min intervals of data. The Shapiro-Wilk normality test was conducted to determine if the data followed normal distributions. Then, we determined the effects of temperature and precipitation manipulations on the soil surface temperature, soil temperature, and soil water content using two-way repeated measures analysis of variance (ANOVA). Paired *t*-tests were performed to verify the differences among treatments. All statistical analyses were performed using SAS (version 9.4; SAS Institute, Cary, NC, USA).

3. Results and discussion

3.1. Extreme heat simulation

The soil surface temperature in T90 reached the target temperature difference approximately 15 min after the heater was operated (Figure 3). For T99, the heaters took approximately 14 min to attain the target difference. The heater maintained the temperature difference (°C, mean ± one standard deviation) of 2.8 ± 0.1 in T90 and 6.1 ± 0.2 in T99, showing a loss of only 0.4 °C in both treatments over 1 h. Weather conditions such as wind and rain can induce temperature losses during the heating period (Kimball and Conley, 2009). The heaters in both treatments occasionally heated the plots above the target temperature. It seems that the heaters contributed residual heat to the plots, even when the relays switched off the heaters. Judging by the greater overheating in T99, the triple heaters in T99 might have caused higher residual heat than the double heaters in T90. The result of minute-by-minute heater performance showed that the heater could consistently hold the targeted difference in the soil surface temperature.

The soil surface temperatures during the first and second extreme heat treatments were significantly different among TC, T90, and T99 ($p < 0.0001$; Figure 4a; Table). The soil surface temperature (°C, mean ± one standard deviation) was 23.0 ± 1.0 in TC, 25.6 ± 1.2 in T90, and 28.8 ± 2.3 in T99 during the first extreme heat treatment. During the second treatment, the soil surface temperature (°C) was 26.6 ± 1.1 in TC, 29.2 ± 1.3 in T90, and 32.3 ± 2.7 in T99. The heaters maintained an increase of 2.7 °C and 5.7 °C in the temperature in T90 and T99 throughout both treatment periods, respectively. The results confirmed

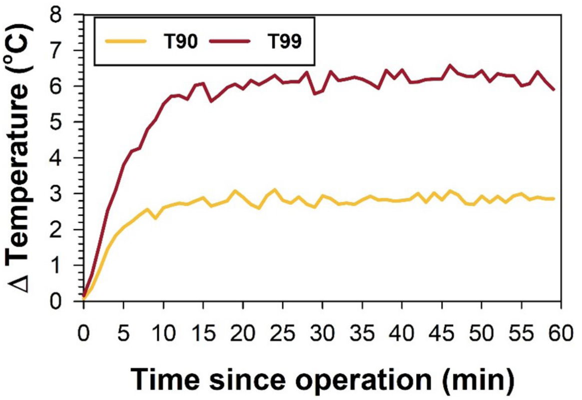

Figure 3. Minute-by-minute differences in the soil surface temperature between heated and control plots for 1 h since the start of heater operation. T90 and T99 indicate treatments simulating the 90th (TX90p) and 99th (TX99p) percentiles of daily maximum temperature during the reference period (1961–2019), respectively.

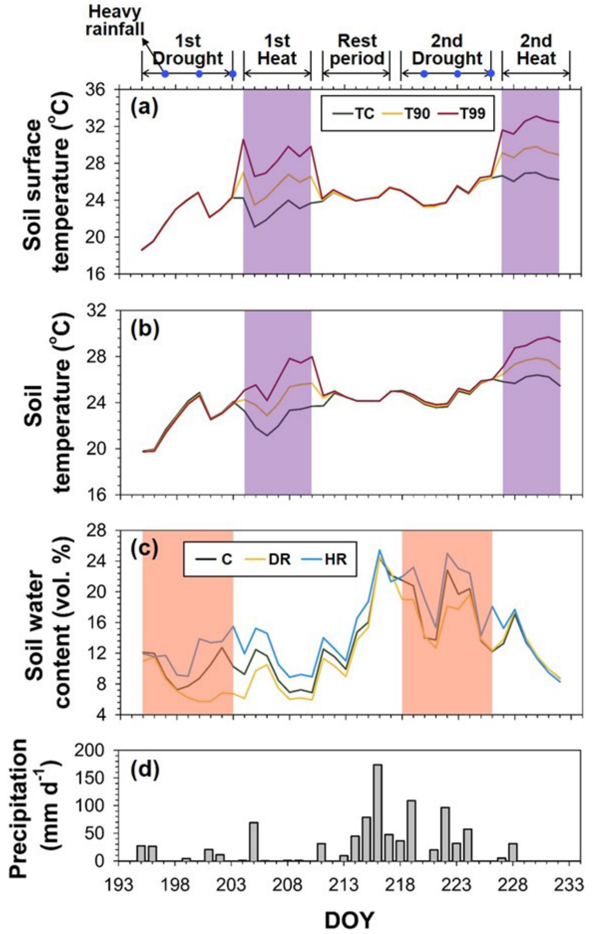

Figure 4. Soil surface temperature (a), soil temperature (b), soil water content (c), daily precipitation (d) during the experimental period. DOY means day of the year. Purple and orange areas indicate the period of heat and drought treatment, respectively. TC is the temperature control, and T90 and T99 indicate treatments simulating the 90th (TX90p) and 99th (TX99p) percentiles of daily maximum temperature during the reference period (1961–2019), respectively. C, DR, and HR are the precipitation control, drought, and heavy rainfall treatments, respectively.

that the temperature manipulation system operated as expected, showing a minimal difference in the soil surface temperature from that of the target.

Abiotic factors, such as rain, might lower the heating capacity of infrared heaters (Kimball et al., 2008). Yun et al. (2014) also reported that the soil surface temperature in the heated plots fell short of the expected temperature under rainy conditions in an open-field experiment which used a single heater. In this study, however, the infrared heating system produced the targeted differences in soil surface temperature even when there was precipitation on DOY 205 and 228 (Figure 4a). Multiple heaters seem to give an advantage to maintaining the targeted temperature.

The soil temperature in each treatment was also significantly different during the extreme heat treatments ($p < 0.0001$; Figure 4b; Table). The soil temperature (°C) was 22.7 ± 1.0 in TC, 24.5 ± 1.2 in T90, and 26.3 ± 1.8 in T99 during the first heat treatment. The soil temperature (°C) during the second treatment was 26.0 ± 0.4 in TC, 27.3 ± 0.5 in T90, and 28.9 ± 0.9 in T99. The significant difference of 1.3–3.6 °C in the soil temperature between the heated and control plots shows that the heating system was able to successfully heat the soil along with the soil surface.

3.2. Extreme drought and heavy rainfall simulation

As soon as the precipitation manipulation began, it rained approximately 28 mm day^{-1} on both DOY 195 and 196 (Figure 4d). However, the rainout shelter was occasionally not closed on the days when it rained intermittently. The soil water content in DR rose slightly on DOY 196 because of the malfunction of the shelter (Figure 4c). Thus, we modified the rainout shelter system to maintain a closed position for 30 min after the last rain detection. The obtained soil water content (vol. %) was 10.1 ± 2.0 in C, whereas it was 7.8 ± 2.2 in DR during the first drought treatment period. From DOY 200 to 204, hourly soil water content (vol. %) ranged from 5.1 to 7.1 in DR and from 7.0 to 18.0 in C (Figure 5a). The soil water content in C tended to rise whenever it rained, whereas rainfall events did not affect soil water content in DR. There was precipitation of 1 mm h^{-1} at 8 AM on DOY 201, and the soil water content in C increased from 7.2 vol. % to 10.6 vol. %. In contrast, the soil water content in DR was maintained at the same value. Precipitation of 16.5 mm h^{-1} increased the soil water content in C from 10.6 to 18.0 vol. %, whereas there was only a small increase in DR.

Table. Results of two-way repeated measures ANOVA and paired t-tests for the soil surface temperature, soil temperature, and soil water content under temperature and precipitation treatments.

Period	Variable	ANOVA				Paired *t*-tests	
		Effect	df	F value	Pr > F	Comparison	Pr > |t|
1st treatment	Soil surface temperature	T	2	35.58	<0.0001	TC-T90	<0.0001
		P	2	1.32	0.2790	TC-T99	<0.0001
		T × P	4	0.89	0.4808	T90-T99	<0.0001
	Soil temperature	T	2	13.05	<0.0001	TC-T90	<0.0001
		P	2	0.73	0.4893	TC-T99	<0.0001
		T × P	4	0.58	0.6758	T90-T99	<0.0001
	Soil water content	T	2	0.72	0.4902	C-DR	<0.0001
		P	2	17.36	<0.0001	C-HR	<0.0001
		T × P	4	0.52	0.7183	DR-HR	<0.0001
2nd treatment	Soil surface temperature	T	2	188.76	<0.0001	TC-T90	<0.0001
		P	2	0.70	0.5017	TC-T99	<0.0001
		T × P	4	1.22	0.3188	T90-T99	<0.0001
	Soil temperature	T	2	12.29	<0.0001	TC-T90	<0.0001
		P	2	1.75	0.1862	TC-T99	<0.0001
		T × P	4	1.06	0.3869	T90-T99	<0.0001
	Soil water content	T	2	0.14	0.8710	C-DR	<0.0001
		P	2	3.86	0.0295	C-HR	0.0474
		T × P	4	0.32	0.8661	DR-HR	<0.0001

df: degrees of freedom; T: temperature; P: precipitation; TC: temperature control; T90: treatment simulating the 90th percentiles of daily maximum temperature; T99: treatment simulating the 99th percentiles of daily maximum temperature; C: precipitation control; DR: drought treatment; HR: heavy rainfall treatment

The soil water content (vol. %) during the second drought treatment was 13.6 ± 2.3 in DR, whereas 18.4 ± 4.4 in C. In the second drought treatment, the initial soil water content was 22 vol. %. Just before the second treatment started, it rained approximately 358 mm for 5 days (DOY 213–217), which was 26% of the mean annual precipitation at the experimental site (Figure 4d). On the first day of the second treatment, the soil water content in DR showed a drastic change, decreasing from 22.6 to 15.6 vol. % despite the rainfall of 37 mm day^{-1} (Figure 4c). The soil water content in C increased slightly from 22.2 to 22.4 vol. % on the same day.

The soil water content in HR greatly increased in accordance with the heavy rainfall treatment. The heavy rainfall treatments were applied on DOY 197, 200, and 203 during the first precipitation manipulation period. On DOY 197, 200, and 203, the soil water content (vol. %) in HR increased from 9.2 to 25.2, 9.6 to 30.8, and 11.8 to 31.9 within 2 h of irrigation, respectively (Figure 5a). Likewise, the soil water content (vol. %) in HR during the second period reached a maximum of 29.7, 30.5, and 29.7 on DOY 220, 223, and 226, respectively, according to the irrigation. Overall, the soil water content (vol. %) in HR was 12.2 ± 2.1 during the first precipitation manipulation period, and 20.3 ± 7.1 during the second period. The soil water content in HR constantly exceeded that in C and DR during the entire precipitation manipulation period from 9 AM on DOY 197 when the first heavy rainfall treatment was applied (Figure 4c). This result showed that the rainfall simulator successfully created the wetter condition in the HR plots than in the C and DR plots.

Soil surface temperature, soil temperature, and soil water content are known to affect each other. For instance, a high temperature may induce a low soil water content as the evaporation rate is high at high temperatures (Abasi et al., 2009). The soil temperature tends to decrease with higher soil water content because moisture can increase the thermal conductivity in soil (Li et al., 2019). In this study, however, temperature manipulation did not affect the soil water content, and precipitation manipulation did not affect the soil surface temperature or soil temperature. This seems to be because the temperature

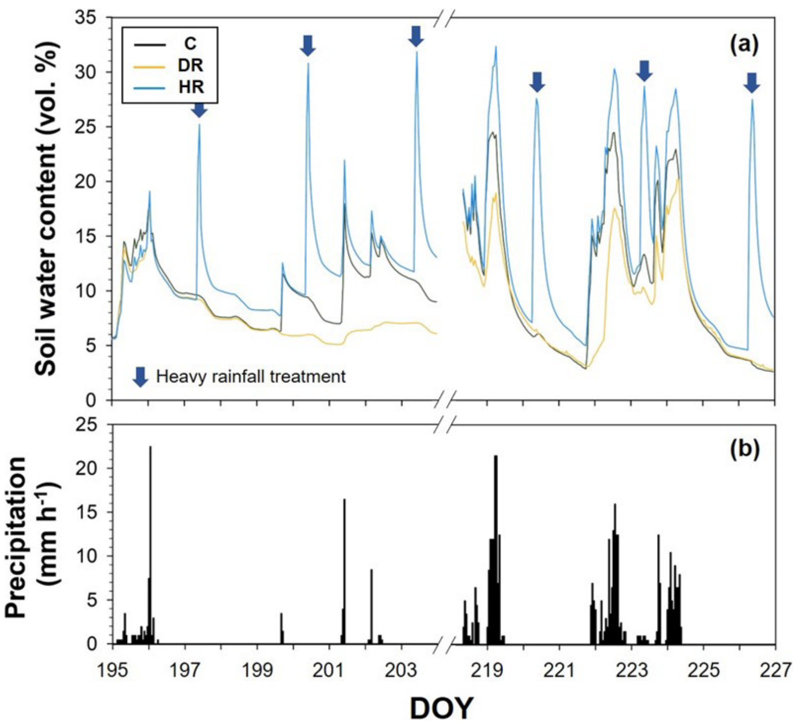

Figure 5. Hourly soil water content (a) and precipitation (b) during the precipitation manipulation period. DOY means day of year. Blue arrow indicates the time of heavy rainfall treatment. C, DR, and HR are the precipitation control, drought, and heavy rainfall treatments, respectively.

and precipitation manipulations were treated separately and not simultaneously.

3.3. Limitations and implications

There were some technical limitations and challenges to simulate extreme climate events in the open field. For the temperature manipulation system, the infrared heaters underheated the specific spots when the heaters cast shadows during the day (Figure 6). However, we tried to produce an equal shading effect for all plots by installing dummies of heaters (Figure 1). We determined this issue as the minor importance since the issue occurred temporarily only when the particular moment during the daytime.

The soil surface and soil temperature in the heated plots tended to be too high when the ambient air temperature corresponded to extreme heat. For example, the daily maximum temperature on DOY 232 was 33.1 °C nearly reaching the defined threshold of TX90p (33.2 °C). Likewise, the effect of extreme drought and heavy rainfall treatment can be doubled unintentionally in the open-field experiment when the long-term drought and heavy rainfall occurred in the study year. Such excessive heating and moisture stresses during naturally occurring extreme climate events could trigger unintended wilting in plants. Jentsch et al. (2007) also demonstrated that natural extreme conditions can present challenges in simulating extreme climate events in open-field experiments. They suggested that the additional controlled simulation of mean past climatic conditions can be a solution for natural extreme climate events.

On DOY 222 and 224, the rainfall increased the soil water content in DR from 10.7 vol. % to 14.6 vol. % and from 14.3 vol. % to 16.8 vol. %, respectively (Figure 4c). It seems that rainfall occurred through the lateral sides of the plots. We considered these as acceptable values, as there are limitations to excluding all rainfall in the open field unless all lateral sides are blocked, such as with an open-top chamber. However, the structures such as the open-top chamber could make the environment of the plot dissimilar to that of the natural conditions in that it causes an increase in the air temperature and air vapor pressure, and a decrease in air movement and transpiration (Kimball et al., 1997). Accordingly, we judged that the disadvantages of the open-top plot outweighed its advantages. It seems that the edge part of plots should be the buffer zone to eliminate the ambient rainfall effect within the DR plots when investigating the plants' and soils' responses to this system.

It is a highly important issue whether the heating system can be adjusted depending on the plant size because to heat too close can damage the subjects unintentionally

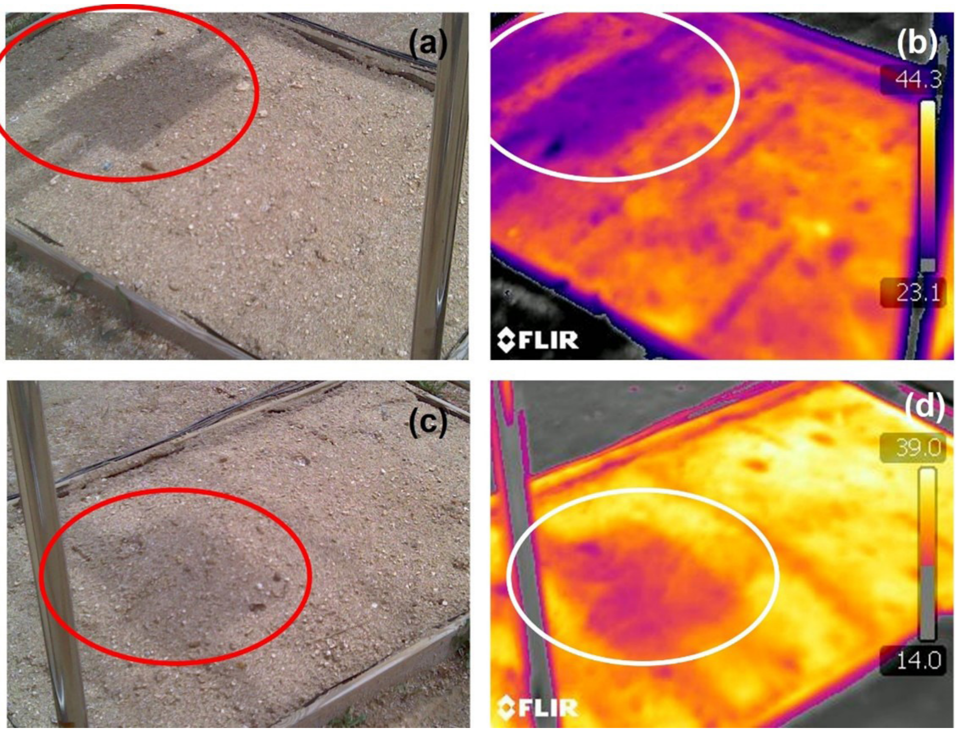

Figure 6. Photographs for the underheated spots (in red/white lined circles) due to the shadow cast by the infrared heater. Thermal images (b and d) of (a) and (c) were photographed with an infrared camera (T335, Teledyne FLIR LLC, Wilsonville, OR, USA).

(Kimball et al., 2017). The heating system in this study can prevent such unintended damage to plants by adjusting the height of steel pipes that hold the heaters (Figure 1). In addition, the targeted temperature of the system can be altered as the scenario and threshold of extreme heat may vary depending on the regions and reference periods. Users can edit the targeted temperature via the data logger programming. Like the temperature manipulation system, the precipitation manipulation system has the advantage to modify the intensity of extreme climate events simulation depending on the regions and scenario. The rainout shelter in this study has the advantage to set the duration for extreme drought simulation since the rainout shelter is automatic. The heavy rainfall simulator also can produce various heavy rainfall scenarios by setting the spraying pressure and applying time on the control panel. The more realistic scenario of extreme climate events can be simulated in the open-field experiment due to the adjustability of our multifactor manipulation system.

There is a need for multifactor experiments to investigate the responses of ecosystems to climate change as the combined multiple factors can cause stronger stresses to ecosystems than the single factor (De Boeck et al., 2015; Beillouin et al., 2020). Furthermore, the single factor experiments can overestimate the effect of climate drivers on ecosystems and cannot investigate the interaction among factors (Mikkelsen et al., 2008; Larsen et al., 2011). The temperature and precipitation manipulation system, devised in this study, could satisfy those necessities in that the system could simulate extreme drought and heavy rainfall during extreme heat. Mikkelsen et al. (2008) who designed multifactor experiments with elevated CO_2, warming, and drought also emphasized that the multifactor experiments are highly important tools to figure out the impacts of interaction among single factors on ecosystems. Furthermore, our system also included the single factor experiment, thereby enhancing mechanistic understanding of abiotic stresses on ecosystems through the comparison between the impact of single and multiple factors (Mikkelsen et al., 2008). De Boeck et al. (2015) expressed concern that multifactor experiments might have a lack of replicates due to cost and workload. However, our system has sufficient replicates (six per treatment), and thus, can have advantages with respect to statistical power. Our multifactor manipulation system may aid developing realistic models on ecosystem functioning to concurrent extreme climate events through understanding the interactive effects.

4. Conclusion

This study was conducted to design an open-field temperature and precipitation manipulation system for simulating summer extreme climate events and to verify its functionality. The infrared heaters increased the soil surface and soil temperatures. In addition, the heaters successfully maintained the targeted temperature difference. We confirmed the functionality of the automatic rainout shelter, which resulted in significant dry conditions. The rainfall simulator also created wet soil conditions with an extremely high soil water content. However, there were some limitations in the current study, such as excessive soil surface and soil heating during naturally occurring extreme climate events and rainfall coming through the lateral sides of the rainout shelter. The system designed in this study can be effectively utilized to research responses of various ecosystems, including plants and soil to extreme climate change. Furthermore, the system has the advantage of applying diverse intensities of extreme climate events by altering the settings of the targeted temperature, spraying pressure, or duration of the operation. Although our system focused on small-sized subjects such as seedlings and herbaceous species, it is necessary to develop an extreme climate events simulation system that can work in the forest to determine the responses of mature trees, understories, soils, or microorganisms in forests based on our system design.

Acknowledgement
This study was carried out with the support of 'R&D Program for Forest Science Technology (Project No. "2020181A00-2222-BB01")' provided by Korea Forest Service (Korea Forestry Promotion Institute).

Conflict of interest
The authors declare that there is no conflict of interest.

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