Title: Data associated with "The Importance of Extreme Rainfall Events and Their Timing in a Semi-Arid Grassland"

Associated publication: Post, A.K. & Knapp, A.K. (2020). The importance of extreme rainfall events and their timing in a semi-arid ecosystem. Journal of Ecology. https://doi.org/10.1111/1365-2745.13478

Abstract: Climate change is intensifying the hydrologic cycle globally, increasing both the size and frequency of extreme precipitation events, or deluges. Arid and semi-arid ecosystems are expected to be particularly responsive to this change because their ecological processes are largely driven by distinct soil moisture pulses. However, since soil moisture, air temperature, and plant phenology vary throughout the growing season, deluges will likely have differing impacts on these systems depending on when they occur. We conducted a field experiment to assess how the seasonal timing (early, middle, or late growing season) of a single deluge (70 mm precipitation event) altered key ecological processes in the semi-arid shortgrass steppe of North America. Regardless of timing, a single deluge stimulated most ecosystem processes, but a deluge at mid-season caused the greatest increase in soil respiration, canopy greenness, aboveground net primary production (ANPP), and growth and flowering of the dominant plant species (*Bouteloua gracilis*). In contrast, belowground net primary production (BNPP) was insensitive to deluge timing, with a consistent BNPP increase in all the deluge treatments that was almost twice as large as the ANPP response. This BNPP response was largely driven by enhanced root production at 10-20 cm, rather than 0-10 cm, soil depths. In a semi-arid ecosystem, a single deluge can have season-long impacts on many ecosystem processes, but responses can be mediated by event timing. Therefore, predicting responses of semi-arid ecosystems to more dynamic precipitation regimes, and subsequent impacts on the global carbon budget, will require knowledge of how deluge magnitude, frequency, and timing are being altered by climate change.

Contact: Alison Post (akpost@colostate.edu)

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Data collection location: USDA-ARS Central Plains Experimental Range (40.8422, -104.7156)

Data collection time period: 2017-05-01 to 2017-09-26

File information: 12 files are included in this folder.

1. “README”. Contains detailed information concerning files 2-12.
File format: .pdf

2. “Precipitation”. Ambient precipitation during experimental period (2017-05-01 to 2017-09-26)
File format: .csv
Variables:

- Date: Date of recorded rainfall. Note: Only dates with rainfall are listed, all unlisted days received 0 mm precipitation.
- Precip (mm): Daily precipitation in mm
- Re-added: Indicates whether rain occurred when rainout shelters were installed

- Y = Precipitation occurred when shelters were in place ("Y"), and was added back to plots at a later date. The listed date is when it was added back.
- N = Ambient precipitation that occurred when shelters were removed

3. "Air temperature". Hourly ambient air temperature (40 cm from ground level) both underneath and outside of shelters during experimental period (2017-05-02 to 2017-09-26).
File format: .csv
Variables:
- iButton ID: Unique identifier for each iButton
- Shelter: Indicates whether the iButton was located underneath a rainout shelter
  - Y = Under rainout shelter
  - N = Not under rainout shelter (ambient)
- Date-Time: Date and time of temperature reading
- Temperature (°C): Recorded temperature in degrees Celsius

4. "Soil moisture". Soil moisture (to 20 cm depth) of plots during experimental period (2017-05-01 to 2017-09-21).
File format: .csv
Variables:
- Date: Date of measurement
- Plot: Plot where measurement was taken (Plots 1-32)
- Trt: Deluge treatment (A = Early-season deluge, B = Mid-season deluge, C = Late-season deluge, D = Ambient)
- VWC: Soil moisture measured as % volumetric water content (VWC), corrected for soil texture of site

5. "Soil respiration". Soil CO_2 efflux and soil temperature (10 cm depth) of plots during experimental period (2017-05-01 to 2017-09-21).
File format: .csv
Variables:
- Date: Date of measurement
- Time: Time of measurement
- Plot: Plot where measurement was taken (Plots 1-32)
- Trt: Deluge treatment (A = Early-season deluge, B = Mid-season deluge, C = Late-season deluge, D = Ambient)
- Avg_Efflux: CO_2 efflux (soil respiration) of the plot (average of 1-2 readings) in µmol CO_2 m^{-2} s^{-1}.
- Soil_Temp: Concurrent measurement of soil temperature to a depth of 10 cm, in degrees Celsius
- VWC: Concurrent measurement of soil moisture to a depth of 20 cm measured as % volumetric water content (VWC), corrected for soil texture of site

6. "ANPP". Aboveground net primary production of the experimental plots, collected at the end of the experimental period (mid-Sept).
File format: .csv
Variables:
- Plot: Plot where sample was collected (Plots 1-32)

- Trt: Deluge treatment (A = Early-season deluge, B = Mid-season deluge, C = Late-season deluge, D = Ambient)
- Rep: Experimental replication of sample (0.1 m^2, 2 reps/plot)
- Grass_mass: Mass of non-reproductive grass in sample, in grams
- Forb_mass: Mass of forbs in sample, in grams
- SH_mass: Mass of *B. gracilis* seedheads (flowering stalks) in sample, in grams
- SH_num: Number of *B. gracilis* seedheads (flowering stalks) in sample
- Grass_Total: Total mass of grass (Grass_mass + SH_mass) in sample, in grams
- Total_biomass: Total mass of the entire sample (Grass_Total + Forb_mass), in grams
- ANPP_total: Aboveground net primary production- Total_biomass corrected for area (g m^{-2})

7. "BNPP". Belowground net primary production of the experimental plots. In-growth cores were installed 2017-05-06 to 2017-09-22.

File format: .csv

Variables:

- Plot: Plot where sample was collected (Plots 1-32)
- Trt: Deluge treatment (A = Early-season deluge, B = Mid-season deluge, C = Late-season deluge, D = Ambient)
- Depth: Depth increment of in-growth core
  - T = Top (0-10 cm)
  - B = Bottom (10-20 cm)
- Mass: Mass of roots in sample, in grams
- BNPP: Belowground net primary production – root mass corrected for area (g m^{-2})

8. "Canopy greenness". Plot greenness from repeat digital photography, as calculated with the green chromatic coordinate (GCC) during the experimental period (2017-05-01 to 2017-09-07).

File format: .csv

Variables:

- Date: Date of measurement
- Plot: Plot where measurement was taken (Plots 1-32)
- Trt: Deluge treatment (A = Early-season deluge, B = Mid-season deluge, C = Late-season deluge, D = Ambient)
- GCC: Average green chromatic coordinate (greenness) of pixels in plot image

9. "Flowering stalk density". Number of *B. gracilis* flowering stalks in each 1-m^2 plot over the course of the experimental period once the first flowers appeared (2017-07-03 to 2017-08-18).

File format: .csv

Variables:

- Date: Date of measurement
- Trt: Deluge treatment (A = Early-season deluge, B = Mid-season deluge, C = Late-season deluge, D = Ambient)
- Plot: Plot where measurement was taken (Plots 1-32)
- num_flowers: Number of *B. gracilis* flowering stalks present in the plot

10. "Leaf length". Number of leaves and leaf length measured on designated *B. gracilis* tillers during the experimental period (2017-06-12 to 2017-09-14).

File format: .csv

Variables:

- Date: Date of measurement

- Plot: Plot where measurement was taken (Plots 1-32)
- Trt: Deluge treatment (A = Early-season deluge, B = Mid-season deluge, C = Late-season deluge, D = Ambient)
- Rep: Experimental replication (3 tillers/plot, A-C)
- num_lvs: Number of green leaves per tiller
- Avg_LH: Average length (in cm) of all green leaves per tiller
- Max_LH: Length (in cm) of longest green leaf per tiller
- Cum_LH: Cumulative length (in cm) of all green leaves per tiller – the length of all the green leaves were summed for each tiller

11. "Water potential". The pre-dawn and midday water potential of *B. gracilis* leaves, as measured before and after each deluge treatment (2017-06-08 to 2017-08-25).
File format: .csv
Variables:
- Date: Date of measurement
- Time: Time of day the measurement was taken
    - PD = pre-dawn (~ 3-4 am)
    - MD = midday (~ 12-1 pm)
- Plot: Plot where measurement was taken (Plots 1-32)
- Trt: Deluge treatment (A = Early-season deluge, B = Mid-season deluge, C = Late-season deluge, D = Ambient)
- WP: Measured water potential in MPa

12. "Species composition". Visual estimate of species composition of all the experimental plots, assessed 2017-07-05 to 2017-07-06.
File format: .csv
Variables:
- Plot: Plot where measurement was taken (Plots 1-32)
- Species: Names of plant species present in plots
- Code: 4-letter code for each plant species'
- % cover: Percent of plot occupied by indicated species, as estimated from visual assessment

Methods:
Site Description

Research was conducted in an undisturbed, native shortgrass steppe ecosystem located at the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) Central Plains Experimental Range (CPER) in Northeastern Colorado (40.8422, -104.7156). Mean annual precipitation is 321 mm, with about 70% occurring during the summer months (May-September); mean annual temperature is 8.6°C (Lauenroth & Sala, 1992). Average ANPP is ~100 g m^{-2} (Lauenroth & Sala, 1992), and the dominant C_4 grass, *Bouteloua gracilis* (blue grama), accounts for up to 90% of total plant cover (Milchunas et al., 1989). Soils at the experimental site are classified in the Ascalon series (Aridic Argiustolls; https://soilseries.sc.egov.usda.gov/) with a sandy clay loam texture (61% sand, 17% silt, 22% clay) and 6.4% organic matter (Soil, Water, and Plant Testing Laboratory, Colorado State University).

Experimental Design and Treatments

We applied a deluge treatment (70 mm event) to 32 1-m^2 plots in a relatively flat location at a site that had been protected from large ungulate grazing for 6 years prior to the experiment. Previously, the site was moderately grazed by domestic livestock (M. Johnston, pers. Comm). Plots were spaced at least 3 m apart and aluminum roof flashing was installed 20 cm outside the perimeter of each plot. Flashing was inserted to a depth of 10 cm belowground and extended 5 cm aboveground. Clear corrugated polycarbonate roofs (Suntuf, Palram Americas, 2.44 m by 3.05 m) were temporarily erected over all the plots during each deluge addition (see below). Thus, there was a 0.7 to 1.0 m buffer between the roof edge and the plot edge. Roofs were installed 1 m above ground-level, and slightly angled to allow for water drainage away from plots.

To assess the influence of the shelters on ambient environmental variables, temperature and light readings were taken both underneath and just outside the shelters. From May 2 – September 25, 2017, hourly air temperature was recorded using iButtons (iButtonLink Technology, model DS1921G) placed within and adjacent to the study plots (n = 2 each). They were shielded from direct sunlight and extended over the plots to measure temperature at the plot center 40 cm above ground level. Photosynthetically active radiation (PAR) was measured just above plant height both under and adjacent to 10 shelters at noon on a sunny day in mid-July using a 1-m linear quantum light sensor (Decagon AccuPAR, model LP-80).

Plots were randomly assigned to one of three deluge treatments or to the Ambient group (N = 8 plots/treatment). The treatments included the addition of a deluge in either the early (June 10-12), mid (July 11-13), or late (August 8-10) part of the 2017 growing season (referred to hereafter as Early, Mid, or Late treatments). Ambient plots did not receive additional rainfall. We analyzed summer (Jun-Aug) precipitation data from a nearby NOAA (Nunn, CO; 40.7063, −104.7833) weather station from 1980-2016 to quantify the statistical distribution of precipitation event sizes and select the magnitude of the applied deluge treatment. For this analysis, we excluded rain events less than 2 mm and combined consecutive rain days into a single rain event, as in this region, rain days tend to be clustered (Bertolin & Rasmussen, 1969) and have an additive effect on ecosystem processes (Loik et al., 2004). Since our goal was to simulate future deluge events that are expected to become larger and more frequent, we chose a statistically extreme 70 mm event (98.6^{th} percentile of historic event size, Fig. S1). We added the deluge over a 3-day period, with 40 mm applied on the first day, and 15 mm on each of the next two days. Water was applied using a hand-held watering wand attached to a flow meter and pump to deliver potable water from a local water delivery service (McDonald Farms Enterprises, Frederick, CO). Added water met US EPA drinking water standards and thus was not a significant source of nitrogen compared to annual atmospheric inputs (Burke et al. 2002; Burke et al., 2008), and well-below critical loads estimated for regional grasslands (Symstad et al. 2019).

To prevent an unpredictable natural rainstorm from confounding the treatments, roofs were erected over all the plots 2-3 days before each deluge addition and remained for 10-12 days after. Roofs were then removed to allow for ambient rainfall the rest of the growing season. The relatively small quantities of ambient rain that fell when the roofs were erected (see results) was added back to all of the plots within one week of the roofs being removed, using the same watering method as described above.

Measured Responses

In all plots, we monitored soil moisture, soil CO_2 efflux (respiration), canopy greenness, and above- and below-ground net primary production (ANPP & BNPP). In addition, leaf growth, leaf water potential, and flowering of the dominant species, *B. gracilis*, was recorded.

Soil moisture and soil respiration were measured weekly for the duration of the experiment (May 1 – Sept 21). More frequent measurements (every 1-3 days) were made immediately following a deluge addition. Soil moisture was measured to a depth of 20 cm in the center of each plot via a time-domain reflectometry (TDR) probe (Campbell Hydrosense II). Values were calibrated to the soil texture of the study site using gravimetric soil moisture measurements of multiple (N = 6) soil cores collected at various soil moisture levels. To monitor soil respiration, permanent PVC collars (10 cm diameter) were installed in bare soil areas, at the mid-point between *B. gracilis* patches. Collars were installed in each plot at the beginning of the growing season to a depth of 2.4 cm and extended 2 cm above the soil surface. Before each measurement, minor amounts of aboveground vegetation within the collar were clipped and removed. Soil CO_2 efflux from each collar was measured at midday (10 am – 2 pm) at ambient CO_2 concentration, temperature, and humidity using a 6400-09 soil flux chamber attached to an LI-6400 (LI-COR, Lincoln, NE). Concurrently, soil temperature was measured just outside of the collar to a depth of 10 cm.

Changes in plot greenness were monitored weekly (excluding weeks when the roofs were in place) via repeat digital photography. For each photograph, the camera (Sony cyber-shot digital camera, model DSC-WX100, 2496 x 1872 pixel resolution) was positioned directly over the center of each plot at a 90° angle, 1.2 m above the ground surface to capture the entire 1-m^2 plot. Each picture was then cropped to the upper right corner (0.25 m^2) of each plot (to avoid the influence of markers elsewhere in the plots), re-sized to standardize the number of pixels (500 x 450 pixels), and then assessed for greenness based on the green chromatic coordinate (GCC) index. This index computes greenness relative to the total brightness of each pixel using the following formula: green / (red + blue + green) (Filippa et al., 2016). By using a ratio, this metric accounts for variation in image lighting. Using the package EBImage (Pau et al., 2010) in R, we calculated the GCC for each pixel in an image, and then averaged all the image pixels to obtain mean GCC.

Because *B. gracilis* accounts for a majority of plant cover in the shortgrass steppe, we focused on growth and flowering of this species. Before the first deluge addition, we marked three *B. gracilis* tillers, each from spatially separate plant crowns, within each plot. Every 1-2 weeks (Jun 12 – Sept 7), all live leaves (at least 50% green) on each marked tiller were counted and measured. For each tiller, the lengths of all the green leaves were summed to obtain a measure of total green leaf length per tiller, which we use as a metric of *B. gracilis* plant growth. The three tillers within each plot were averaged to obtain a plot-level value. The Late treatment plots were measured one additional week (Sept 14) since tillers in this treatment remained green longer. Upon the appearance of the first *B. gracilis* flowering stalks in early July, we counted the number of flowering stalks in each plot weekly through mid-August. We completed visual assessments of plant species cover within each plot in early July to use as a covariate in the analysis of *B. gracilis* flowering density.

To monitor the influence of the deluges on plant water status, pre-dawn and midday leaf water potential of *B. gracilis* were measured. Measurements were made 1-2 days prior to each deluge treatment, the day after water additions concluded, and once a week for the next two weeks thereafter. Measurements were only made on the plots actively receiving a treatment at the time and in the Ambient plots (N = 8 plots each), therefore, three sets of measurements were made during the growing season coinciding with the Early, Mid and Late deluge treatments. Leaf water potential was measured with a Scholander pressure bomb (PMS instruments) on 1-2 leaves per plot.

Belowground net primary productivity (BNPP) was measured using 20 cm depth root in-growth cores (Pérez-Harguindeguy et al., 2013). This depth was chosen as it has been shown that 75% of roots at this site are found within the top 20 cm of the soil profile (Milchunas & Lauenroth, 1989). The cores were made from 2 mm fiberglass window screen formed into hollow cylinders 22 cm in length with a diameter of 5 cm. Soil was collected from a location adjacent to the study site to a maximum depth of 20 cm. Soil was then air dried, sieved, and hand-picked to remove any remaining roots prior to filling the mesh cylinders. One core per plot was installed on May 6, 2017 to a depth of 20 cm (2 cm remained above the soil surface). To standardize, all cores were placed in between grass crowns. Cores were removed at the end of the growing season in mid-September and temporarily stored in plastic bags at 40°C. During processing, cores were cut in half so that root production could be assessed at two depth intervals, 0-10 cm and 10-20 cm. Each segment was then washed through two sieves (2 mm & 0.5 mm), and roots on the larger sieve were collected. In order to separate smaller roots from other detritus, material left on the smaller sieve was rinsed into a bin of water and roots floating at the surface were hand-picked. All roots were dried in a 60°C oven for two days and then weighed to the nearest 0.0001 g.

At the end of the growing season (mid-Sept), all plots were sampled for aboveground net primary productivity (ANPP). In each plot, we harvested all biomass within two 0.1 m^2 quadrats. During this process, biomass was sorted by functional group (grass, forb) and *B. gracilis* flowering stalks were separated. All biomass was dried at 60°C for two days, and then sorted to remove biomass from previous years (distinguished by grey color). Samples were weighed to the nearest 0.01 g.

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