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Conversion of encroached juniper woodland back to native prairie and to switchgrass increases root zone soil moisture and watershed runoff

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ABSTRACT

Mechanical removal of encroached juniper (*Juniperus* spp.) is a common practice to restore native grasslands. However, the hydrological responses to grassland restoration remain mostly unquantified for the climate transition zone in the southern Great Plains of the USA where ecosystem evapotranspiration is highly sensitive to the change of vegetation functional type. We used a paired watershed approach to directly quantify the impact of mechanical removal of eastern redcedar (*Juniperus virginiana* L., redcedar) and restoration to native prairie or establishment of switchgrass (*Panicum virgatum* L.) on root zone soil moisture and event-based runoff for eight years including three main phases - calibration, transition, and restored grassland in north-central Oklahoma, USA. Results showed that the root zone soil water storage on average increased 1.6 and 1.9 times for restored prairie and switchgrass, respectively, after juniper removal. The regression model estimation based on the relationships established in the calibration phases between event-based runoff from control watershed and the treatment watersheds found that the restored prairie and switchgrass production system increased annual runoff by 4.46 and 4.54 times, respectively. These results indicated that both soil moisture and runoff are highly responsive to land use change in the southern Great Plains. Reestablishment of herbaceous dominance by mechanically removing encroached woody species is closely followed by restoration of soil moisture dynamics and watershed runoff regime.

1. Introduction

Change in land surface condition and increased climate variability impose a great challenge on sustainable management of watersheds and water resources in the climate transition zone of the southern and central Great Plains, USA (Ojima et al., 1999; Sun et al., 2008). An important land surface change in this region is associated with the transition from herbaceous plant dominance to woody plant dominance characterized by a juniper species (*Juniperus virginiana* L., eastern redcedar or redcedar) encroachment in the prairie and oak savannas of the central Great Plains (Briggs et al., 2005; Hoff et al., 2018). This transition is associated mainly with a disruption of the historical fire regime and causes a decline or loss of prairie productivity (Norris et al., 2001; Ganguli et al., 2016), plant biodiversity (van Els et al., 2010), and avian and mammalian biodiversity (Horncastle et al., 2004). Importantly, the soil moisture dynamics are substantially altered and water yield is reduced (Zou et al., 2014; Qiao et al., 2017; Acharya et al., 2018). Mechanical removal of juniper trees is an effective approach to quickly reclaim encroached land parcels (Morton et al., 2010). However, site disturbance associated with mechanical operations could cause excessive surface runoff and potential soil erosion if not appropriately managed. Also, after juniper removal, the watershed will revegetate and can restore to prairie naturally or be planted with species such as switchgrass (*Panicum virgatum* L.) for biomass production. However, it is unknown how the root zone soil moisture condition and runoff regime will differ between pre- and post-treatment conditions, and between these two potential land use options that both restore herbaceous plant dominance.

Due to reduced evapotranspiration, reducing woody canopy can increase streamflow in the semiarid and subhumid regions in the USA (Zou et al., 2010; Madsen et al., 2011; Madsen et al., 2012; Roundy et al., 2014). However, there is a limitation regarding the vegetation-induced change in evapotranspiration (ET). The magnitude of vegetation-induced change is likely the greatest where precipitation approximately equals potential evapotranspiration (PET) (Zhang et al., 2001; Huxman et al., 2005). In wetter areas where precipitation

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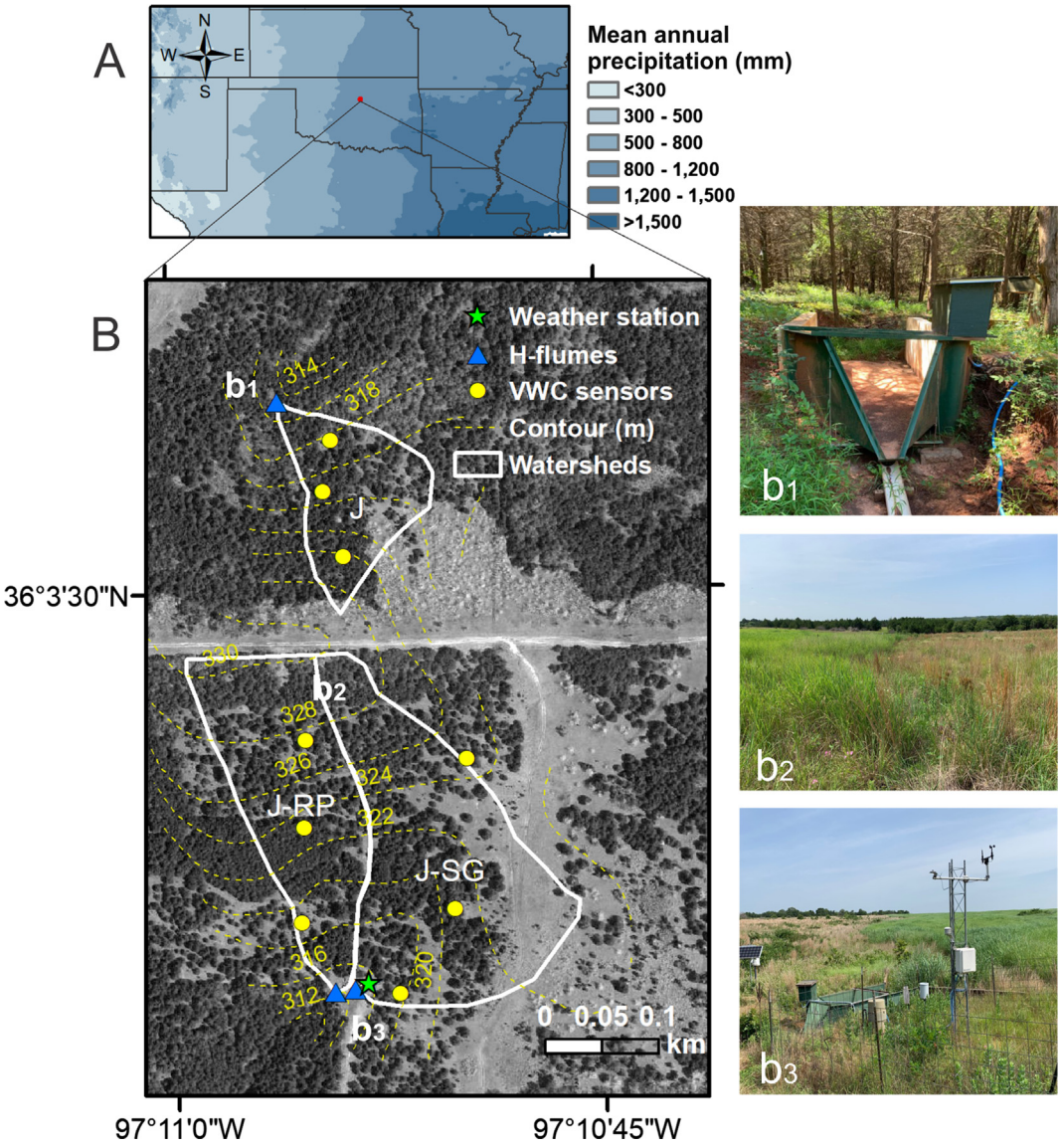


Fig. 1. Mean annual precipitation from 1981 to 2010 across Oklahoma, USA (precipitation raster GIS data were obtained from the PRISM climate group), and the approximate location of the study site in the Cross Timbers of north-central Oklahoma (A). The juniper cover of the study site before treatment (based on Google Earth image taken in February 2014) (B). The three experimental watersheds (*J*, *J-RP*, *J-SG*) were in upland locations (B). The watershed boundaries were delineated manually using a land surveying laser level, GPS units, and ground-truthing by manual observation of surface flow paths. The contour lines shown were generated in ArcGIS 10.5 by using the Lidar 2-meter data for a visualization purpose. The soil moisture arrays with four volumetric water content (VWC) sensors were distributed at the upper, middle, and lower position of each watershed. The intact control juniper watershed (*J*) had no treatment (b_1). *J – RP* watershed was restored to native prairie, and *J-SG* watershed was converted to switchgrass (b_2). The weather station was close to the H-flume in the watershed *J-SG* (b_3).

exceeds PET, vegetation change may have less effect because excess precipitation causes runoff while in drier areas, a large deficit between precipitation and PET causes runoff events to be rare (Huxman et al., 2005). In low precipitation regions, several recent studies showed that woody canopy removal did not result in a measurable increase in streamflow (Guardiola-Claramonte et al., 2011; Biederman et al., 2015; Williams et al., 2018) and that streamflow did not increase in most basins following the loss of tree canopy due to tree die-off (Biederman et al., 2015). The current consensus is that the effect of tree or brush removal on the streamflow is minimal where annual precipitation is < 500 mm (Archer and Predick, 2014). In contrast, deforestation in high precipitation regions has been a significant contributor of soil erosion, and large scale deforestation in the cloud forest and tropical rainforest may even reduce runoff by suppressing the positive feedback between soil moisture and precipitation (Junkermann et al., 2009; Lawrence and Vandecar, 2015).

Consequently, vegetation change should have maximal hydrological consequences in the forest and grassland transition zone such as the southern and central Great Plains of the USA encompassing a precipitation gradient from 500 mm to 1000 mm (Fig. 1A). As the climate in the transition zone is becoming more variable and the demand for water continues to increase, control of invasive and encroaching woody species to increase streamflow is an important consideration. However, the effectiveness of woody vegetation removal within the forest and grassland transition zone (e.g., the southern and central Great Plains) remains unknown. For this region, increases in the runoff after woody vegetation removal have been generally estimated through hydrological modeling (Afinowicz et al., 2005), with few empirical data to verify modeling conclusions.

The impact and response of experiments measuring runoff after removing trees could be subject to three types of uncertainties. Failure to detect the change in runoff after tree removal could result from the

mismatch in scale between the treatment area and the total area contributing to streamflow (Wilcox et al., 2006; Biederman et al., 2015; McDonald et al., 2015). Also, how the woody vegetation regrowth or regeneration is managed after harvesting could affect the runoff response (Biederman et al., 2015). If woody plants re-sprout and reoccupy the same area, the positive effects of tree removal on runoff could be transitory. Finally, the trends and variability of climate, particularly precipitation prior to and post-treatment, could confound the results. However, a paired watershed approach overcomes these shortfalls by building the potential difference of watershed behavior and climate variability during the calibration and treatment period into the analytical solution (Brown et al., 2005). At the experimental watershed scale, the land use can be experimentally controlled and its impact directly quantified, providing opportunities to disentangle the impact immediately after disturbance and the altered land use (Bosch and Hewlett, 1982; Clausen et al., 1996; Ali et al., 2017). Paired watershed designs have been widely used to determine the impacts of forest harvesting on the water yield (Bosch and Hewlett, 1982; Brown et al., 2005; Ochoa-Tocachi et al., 2018). However, their application for assessing the impact of woody encroachment and removal on hydrological processes is limited because multi-year, pre-treatment runoff data to establish the calibration regression line are rarely available.

Streamflow is usually a small component in the water budget and is highly variable in a water-limited system. However, overland flow and streamflow regimes are closely associated with root zone soil moisture of which the temporal dynamic is greatly influenced by the plant functional type (Huxman et al., 2005; Liu et al., 2017). Improvement in root zone soil moisture is indicative of the increased runoff and recharge potential at the local scale (Dekker and Ritsema, 1994; Doerr et al., 2000; Acharya et al., 2018). An increase in soil water storage and recharge was documented after removing western juniper (*Juniperus occidentalis*) in Idaho (Seyfried and Wilcox, 2006) and a 20% greater over-winter soil water accumulation after western juniper removal was reported in Oregon (Mollnau et al., 2014). Ultimately, the increase of root zone soil moisture may profoundly affect the responsiveness of the land surface to precipitation and increase the surface runoff coefficient (Sriwongsitanon and Taesombat, 2011; Qiao et al., 2017).

For prairie lands that have been encroached by woody vegetation in the Great Plains, the potential of recovery of streamflow depends on the re-vegetation and land use after woody vegetation removal. A common management approach is to leave the land to restore to native prairie for cattle grazing, although it is subject to encroachment by woody plants again without subsequent management. Alternatively, the land can be actively managed for hay and other biomass production. Switchgrass, an herbaceous species, has been promoted as a potential biofuel feedstock and is highly adapted to the southern United States. Switchgrass can be established by seeding with no-till drilling techniques along with herbicide application under non-drought conditions (Casler et al., 2015). These two conditions, i.e., native prairie and switchgrass production system, may differ in runoff generation as they vary in factors such as plant composition or species diversity, leaf area, rooting depth, and litter cover.

The overall goal of this study was to assess the hydrological response to mechanical removal of juniper followed by restoration to prairie or planted to switchgrass in the south-central Great Plains using a paired watershed approach. The specific objectives included: i) Assess the state change in root zone soil water storage during the land use transition and restored grassland phase (restored native prairie and established switchgrass); ii) Quantify runoff responses during the transition phase and the restored grassland phase; iii) Compare runoff between the juniper woodland converted to restored prairie and juniper converted to switchgrass production system.

2. Materials and methods

2.1. Study area and land use history

The study was conducted in the Cross Timbers Research Range (CTER), which is managed by Oklahoma State University (Fig. 1). The study site is located 15 km southwest of Stillwater, Payne County, Oklahoma, USA (36°3′46.73″ N, 97°11′3.33″ W). The soils are well drained, consisting predominately of the Stephenville–Darnell complex, Coyle soil series, and Grainola–Lucien complex. The average depth of soil is approximately 1 m underlain by sandstone substrates. The site was previously cultivated and allowed to recover to prairie after agricultural abandonment in the 1950 s. The land is currently being managed for research purposes related to prescribed fire, grazing, and watershed hydrology. Fire and grazing interactions through patch-burning have been studied in parts of the research range since 1983 (Fuhlendorf and Engle, 2004). Native tallgrass prairie has been maintained due to burning treatments whereas juniper was present in some areas before the prescribed fire and has heavily encroached many other areas of CTER where burning has been excluded. The site also contains areas of post oak (*Quercus stellata*) dominated woodland as well as prairie lightly encroached by woody vegetation. In this study, we chose to use three previously established juniper-encroached experimental watersheds which have been monitored since 2010 (Qiao et al., 2015). These watersheds range from 1.34 to 3.79 ha (Table 1; Fig. 1).

2.2. Data collection

2.2.1. Meteorological observations

Meteorological observations were continuous since 2011. A weather station was located approximately 5 m east of the H-flume of watershed *J-SG* (Fig. 1). Precipitation was measured with a TB3 siphoning tipping bucket rain gauge with 0.254 mm per tip (Hydrological Services America, Lake Worth, FL, USA). Air temperature and relative humidity were measured at 2 m using a Vaisala Temperature/RH Probe (HMP50, Campbell Scientific Inc, Logan, UT, USA) with an RM Young 6-plate radiation shield. Wind speed and direction (RM Young Company Wind Sentry Set, Traverse City, MI, USA) and solar radiation (Apogee SP-110, Apogee Instruments, Inc., Logan, UT, USA) were measured at 3 m

Table 1
Watershed characteristics of the intact control watershed *(J)*, the cut watershed allowed to restore to native prairie *(J-RP),* and the cut watershed converted to switchgrass *(J-SG)*. The *J* watershed was measured in January 2016 and the *J-RP* and *J-SG* were measured in January 2015.

Watershed	Area (ha)	Slope (%)	Juniper basal area (m^2 ha^{-1})	Juniper density (trees ha^{-1})	Soil types
J	1.34	0–5	17.97	1103	Coyle and Zaneis soils (55.75%); Stephenville-Darnell complex (22.42%); Grainola-Lucien complex (21.83%)
J-RP	2.57	0–5	13.18	863	Stephenville-Darnell complex (77.75%); Renfrow and Grainola soils (11.00%)
J-SG	3.79	0–4	8.66	1533	Stephenville-Darnell complex (29.31%); Renfrow and Grainola (29.02%); Coyle-Lucien complex (20.08%); Grainola-Lucien complex (13.04%)

height.

2.2.2. Root zone soil water

Root zone soil water for each watershed was measured using three soil moisture arrays established in 2010 and distributed at the upper, middle, and lower position of each watershed (Fig. 1). Each array was composed of one EM50 datalogger and four ECH_2O EC-5 capacitance probes (Meter Group Inc., Pullman, WA, USA) installed at depths of 50, 200, 450, and 800 mm to capture the mean condition of soil volumetric water content (θ) every 15 min for the soil layers of 0–100, 100–300, 300–600, and 600–1000 mm, respectively. ECH_2O probes measured the dielectric constant of the soil, which was converted to volumetric water content using the manufacturer's calibration relationship. The EC-5 sensors run at a high measurement frequency which allows a single calibration equation to be used for mineral soils of various textures and electrical conductivities. The accumulated root zone soil water storage (SWS, mm) in the upper 1 m soil profile was calculated based on soil water in each soil layer (Zou et al., 2014). The average of SWS from the three arrays was used to represent the average root zone soil water storage for the watershed.

2.2.3. Runoff

Runoff from each watershed was gauged using a 0.9 m H-flumes. The stage level in the flume was measured at 5-minute intervals using an optical shaft encoder with a minimum stage reading and resolution of 3.0 mm (50386SE-105, HydroLynx, West Sacramento, CA, USA). Stage level readings were converted to discharge values using the known stage-discharge relationship for the given H-flume and discharge was converted to runoff depth using the watershed areas. Annual runoff values, treatment period values, and event-based values were generated by summing the 5-minute data for the period of interest. Two conditions were used to determine the end of runoff events. Most commonly, event end was considered as the last flow record with no further flow reading for a minimum of 24 h in any of the watersheds. For rare cases where the flow did not completely cease before the next precipitation event, the end time of runoff was set as 5 min before the start of the next precipitation event to separate runoff events.

2.3. Treatment design

Paired watershed studies have been widely used to determine the impact of changes in land use or vegetation change on water yield (Bosch and Hewlett, 1982; Hibbert, 1983; Brown et al., 2005; Neary, 2016; Ochoa-Tocachi et al., 2018). This approach involves the use of two nearby watersheds similar in size, topography, soils, and land use. The quantitative relationship of runoff from these two similar, paired watersheds established when the land use or land cover was relatively stable or unchanged for multiple years, is considered the calibration phase. One of the watersheds is subsequently subjected to a treatment (i.e., land use change or land cover change) and the other remains as a control. This allows the yearly climatic variability to be accounted for in the analysis such that change in the quantitative runoff relationship between the paired watersheds is attributed to changes in land use or vegetation type (Brown et al., 2005).

During July 2015, all juniper trees in two adjacent watersheds south of the control watershed were cut using a skid steer equipped with a Marshall tree saw (Tulsa, OK, USA) (Table 2). Cut trees were left to dry on site until January 2016 when they were ground and hauled off site. Grinding and removal were completed by the end of February 2016. One treatment watershed was left to revegetate without further treatment and assigned "juniper to restored prairie" watershed and abbreviated as *J-RP* (Fig. 1). The other cut watershed was further treated with glyphosate herbicide beginning in May 2016 to kill vegetation until May 2017 when an upland switchgrass variety, Alamo, was seeded using a large drilling machine. This watershed was assigned as "juniper to switchgrass" watershed and abbreviated as *J-SG* (Fig. 1). The treated watersheds were fenced to prevent cattle grazing and trampling. The watershed north of the treatment watersheds was not treated and was used as the control (juniper) watershed and abbreviated as *J* (Fig. 1).

Collectively, there were two control vs treatment pairs (*J* vs. *J-RP* and *J* vs. *J-SG*) and the effects of the treatments were compared using the paired-watershed approach. In the pre-treatment period, *J* had the highest juniper basal area, while *J-SG* had the highest density (Table 1). The calibration phase was four years and nine months from Oct 2010 through June 2015 with no management activities on any of the three watersheds (Table 2). To address our objectives, the treatment period was further separated into a transition phase and a restored grassland phase. The transition phase was defined as the period after juniper cutting and before the new vegetation cover was fully established. The restored grassland phase includes restored prairie and established switchgrass. The first year after cutting of the *J-RP* (May 2016 to April 2017) was assigned to the transition phase because of little vegetation cover and biomass growth in the first year of recovery as compared to the second year when more herbaceous vegetation occurred. Likewise, the first year after juniper cutting for the *J-SG* watershed was considered transition as switchgrass was not planted until the following spring.

2.4. Data analysis and statistics

Daily reference evapotranspiration (ET_0) was calculated based on local, daily weather station data using the FAO Penman-Monteith method (Cai et al., 2007). A generalized additive model (GAM) was used as a scatterplot smoothing function for climate variables, which gave a general idea of the trend for weather variables. The Mann-Kendall test was used to quantify the trend of climate variation during the study period (Mann, 1945; Mondal et al., 2012). In the Mann-Kendall test, τ represented the measure of the strength of the trend of climate variation in a time series, with a range from -1 to 1. This value represented the strength and direction of association that exists between climate and time series. The larger absolute value means larger strength between time and climate. A negative value stands for a decreasing trend, while a positive value stands for an increasing trend. We used $\alpha = 0.05$ in this research. We used the time series of SWS of treatment watersheds (*J-RP* and *J-SG*) minus that of the control watershed *J* to calculate the time series of ΔSWS. Then change point detection (Cho and Fryzlewicz, 2015) was applied to check whether there was an increase or decrease in the time series of ΔSWS following treatments. Both the Mann-Kendall test and change point detection were performed in RStudio.

We determined the treatment impacts by testing whether the linear relationship of event-based runoff depths between control watershed and the treatment watershed significantly changed in the transition phase and the restored grassland phase (we tested the significance of changes in slope and intercept between the appropriate sets of regression lines in different phases). Runoff in our experimental watersheds was predominantly from stormflows. Some small rainfall events produced runoff for one watershed but not for the others. For this analysis, we dropped runoff events when there was zero runoff in any of the paired watersheds (*J* vs. *J-RP; J* vs. *J-SG*) which allowed the square root transformation of the event-based runoff data to satisfy the linear regression analysis assumptions: the error terms are normally distributed and the paired data have equal variance. Impact of mechanical removal of juniper on runoff was calculated as the ratio of observed annual runoff to estimated annual runoff in the treatment phase (Clausen et al., 1996). The estimated runoff for the manipulated watersheds was modeled based on the relationship of square root event-based runoff established during the calibration phase assuming the juniper trees were not removed.

Table 2
Timeline of treatments for the cut watershed allowed to restore to native prairie (*J- RP*) and the cut watershed converted to switchgrass (*J-SG*) for the water years 2011 to 2018 (* indicates a time period used in the regression analyses testing difference for runoff events).

Phase	Time	*J-RP*	*J-SG*
Calibration	Oct. 2010–Jun. 2015*	Pretreatment	Pretreatment
Transition	Jul. 2015*	Cut	Cut
	Aug. 2015–Jan. 2016*	Dry	Dry
	Feb. 2016–Apr. 2016	Juniper removal and land idle	Juniper removal and land idle
	May 2016–Mar. 2017*	Recovery to prairie	Herbicide spraying
	Apr. 2017	Recovery to prairie	Plant switchgrass
Restored grassland	May, 2017–Sep., 2018*	Restored prairie	Established switchgrass

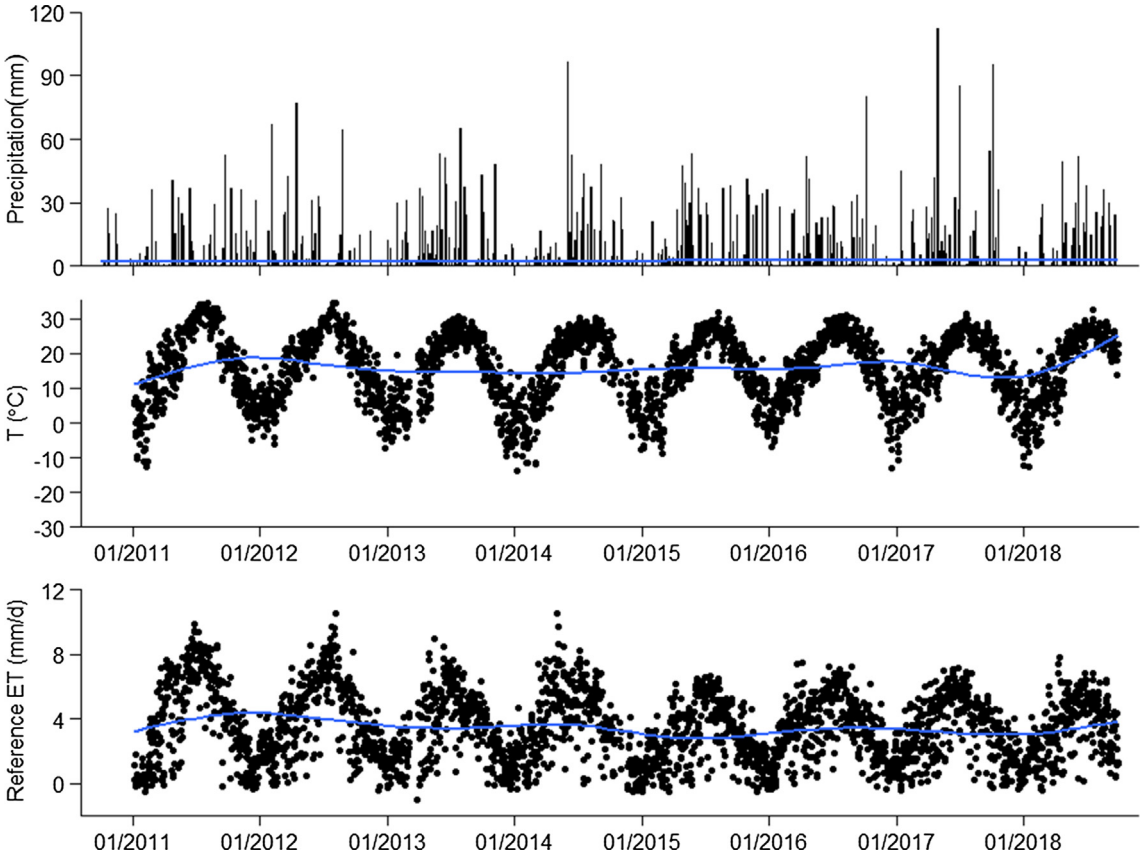


Fig. 2. Daily precipitation, daily mean temperature, and daily reference evapotranspiration from the water years 2011 to 2018. The blue lines are the weighted regression trend lines. The daily precipitation trended up (τ = 0.031, p = 0.027), there was no significant trend in the daily temperature (p = 0.18), and the daily reference ET trended down (τ = -0.066, p < 0.001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Climatic dynamics

The mean annual precipitation was 832 ± 143 (mean ± standard deviation, SD) mm for the eight water years from October 2010 to September 2018. The highest daily precipitation of 112 mm occurred in May 2017 (Fig. 2). The precipitation during the study trended up (p = 0.027) with a positive but small τ value. There was no significant trend in the daily temperature (p = 0.18). The highest daily ET_0 of 11 mm occurred in May 2014 and the mean daily ET_0 was 3.46 ± 2.16 mm for the study period. The daily ET_0 trended down (p < 0.001) with a negative small τ value.

3.2. Root zone soil water storage

The SWS within the 1000 mm soil profile in the control watershed (*J*) was generally less than that in *J-RP* and *J-SG* for the entire study period. During the calibration phase, mean daily SWS in *J* was 143 ± 45 mm (mean ± SD), 267 ± 55 mm in *J-RP* and 216 ± 52 mm in *J-SG* (Fig. 3a1 and 3b1). In the transition and restored grassland phases, mean daily SWS was 163 ± 42 mm in *J*, 356 ± 53 mm in *J-RP*, and 303 ± 37 mm in *J-SG* (Fig. 3a1 and 3b1). The difference in SWS (ΔSWS) increased for both comparisons (Fig. 3a2 and b2). For the *J – J-RP* pair, a change point in the ΔSWS was detected on August 22, 2015. The ΔSWS averaged 125 ± 21 mm before August 22, 2015 and increased to an average value of 195 ± 40 mm after that date (Fig. 3a2). For the *J – J-SG* pair, a change point in the ΔSWS was detected right after cutting of juniper. It averaged 74 ± 28 mm before July 6, 2015 and increased to an average value of 141 ± 36 mm after that date (Fig. 3b2). There was no change point detected for ΔSWS between the transition phases and the restored grassland phases.

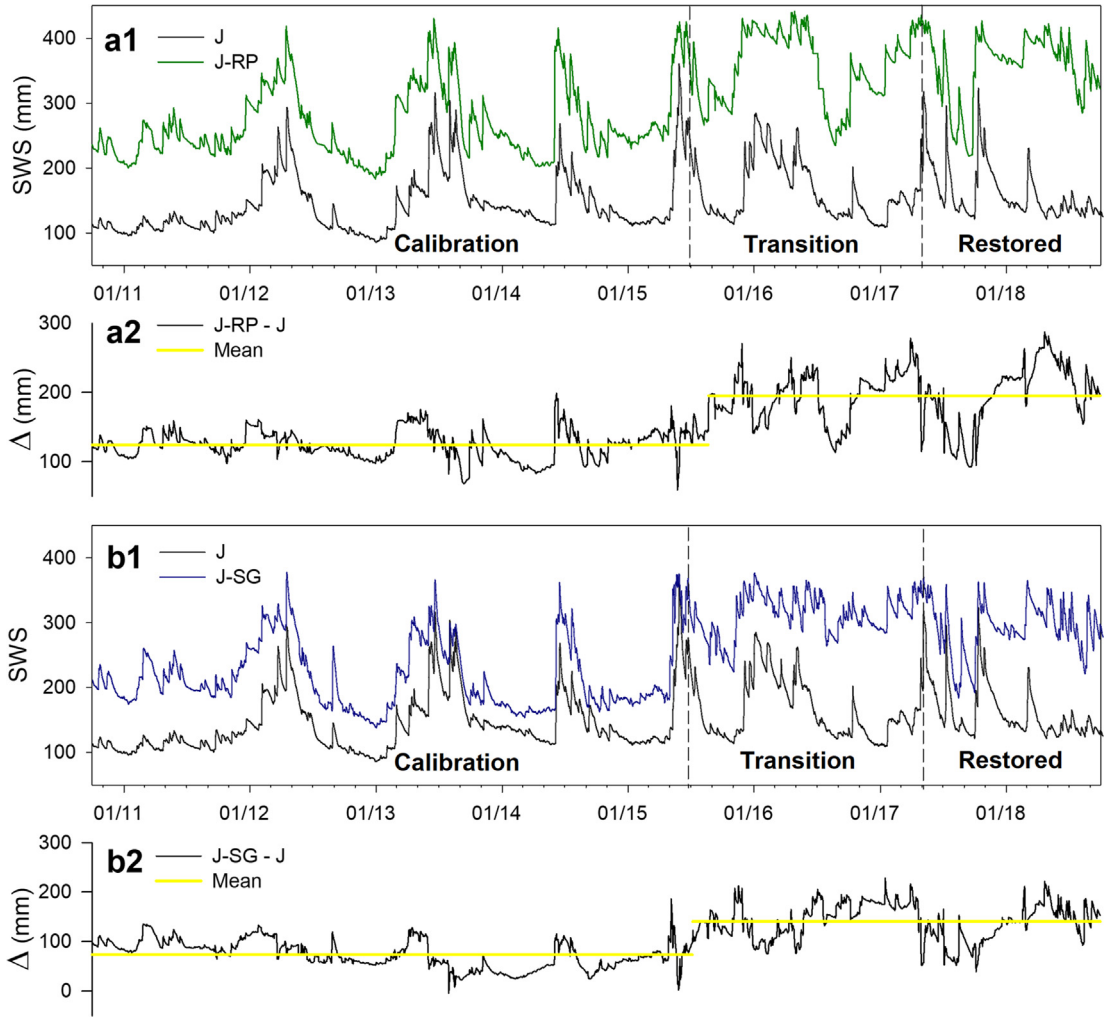


Fig. 3. Daily variation of root zone soil water storage (SWS) in the soil profile (1000 mm) of the paired watersheds; *J* vs. *J-RP* (a1) and *J* vs. *J-SG* (b1), and difference in daily SWS (Δ) between paired watersheds;— *J-RP* – *J* (a2) and *J-SG* – *J* (b2) during the study period (water years 2011 to 2018). Yellow lines represent the mean values of the ΔSWS in different periods separated by the change point. *J*: the intact control watershed of juniper; *J-RP*: the cut watershed allowed to restore to native prairie *(J-RP); J-SG:* the cut watershed converted to switchgrass *(J-SG).* (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Annual runoff and hydrograph

Annual runoff depth varied greatly among water years and the type of land use, ranging from negligible (< 1 mm) runoff in 2011 to over 150 mm in 2017. Annual runoff depth in the control (*J*) was 21 ± 12 (mean ± SD) mm, 9 ± 5 mm in *J-RP* and 16 ± 10 in *J-SG* during the calibration phase (2011–2015) (Fig. 4). After juniper cutting in July 2015, the runoff of the treated watersheds increased relative to the control and remained elevated throughout the tranistion and grassland recovery phases. In 2016–2018, average annual runoff depth in *J* was 27 ± 22 mm, in *J-RP* was 94 ± 49 mm and in *J-SG* was 131 ± 73 mm.

For all time periods except the cut and drying phase for the *J-SG* watershed, the slopes of the relationship between the treated and control watersheds for event-based runoff were signficant (Table 3, Fig. 5). During the calibration phase, the regressions comparing *J* to *J-RP* and *J* to *J-SG* had strong, linear relationships with high coefficients of determination (R^2) (Table 3, Fig. 5). For the comparisons between the *J-RP* and *J* watersheds, the slopes during the cut and drying, recovery to prairie, and restored prairie phases were all signifcantly greater than during the calibration phase indicating an increase in runoff depth with treatment (Table 4, Fig. 5a, c, e) The greatest slope occurred during the recovery to prairie phase (Table 3). Intercepts were signficantly greater for regressions during the the cut and drying and during the restored prairie phases than during the calibration phase (Table 4). For the *J-SG* vs. *J* comparison, the slopes were greater during the herbicide and during the established switchgrass phases than during the calibration phase (Table 4, Fig. 5d and f). The greatest slope occurred during the herbicide phase when vegetaion was absent (Table 3). Intercepts were signficantly greater for regressions during the herbicide and the established switghgrass phases than during the calibration phase (Table 4). During the established grassland phases, (May 2017 through September 2018), the total runoff depth based on the regression model increased by 4.46 fold for the restored prairie and 4.54 fold for the switchgrass production systemcompared to the noncut control watershed.

During the calibration phase, the hydrographs in all three watersheds resembled each other in terms of peak flow and runoff duration. Following a 62 mm storm, for example, event peak flow in *J* was the highest, followed by *J-SG* and *J-RP* (Fig. 6a). The flow duration was comparable and ranged from 35 to 45 h. In the restored grassland phases, the hydrographs of *J-PR* and *J-SG* diverged from that of *J*. For example, a storm event of 27 mm had a the peak flow in *J* that was the lowest and lasted for only 2 h while the peak flows and flow durations of *J-RP* and *J-SG* were much higher with much longer, delayed flow (Fig. 6b).

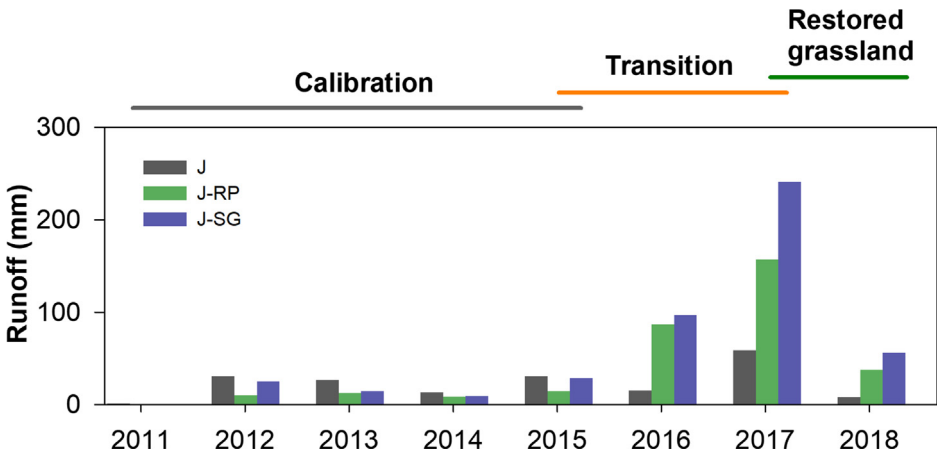


Fig. 4. Annual runoff depth from *J, J-RP* and *J-SG* watersheds during the calibration, transition, and restored grassland phases for water years 2011 to 2018. *J*: the intact control watershed of juniper; *J-RP*: the cut watershed allowed to restore to native prairie *(J-RP); J-SG:* the cut watershed converted to switchgrass *(J-SG)*.

4. Discussion

4.1. Increase in soil moisture and runoff under transition phase

Cutting juniper reduces the tree transpiration component of the water budget. Although an increase in soil moisture after shrub and tree removal is often attributed to reduced canopy interception (Taucer et al., 2008), the increase in soil moisture as observed in this study was likely primarily due to reduced transpiration since the cut trees were initially left on site and could continue to intercept rainfall. Caterina et al. (2014) found that juniper can transpire almost all throughfall during a year of normal precipitation. Initially, after cutting, there was little herbaceous component as it had been previously suppressed by the tree canopies. In addition, prior to removal, the cut juniper continued to shade the soil and suppress herbaceous plant development.

After February 2016, the removal of the dead juniper from the cut watersheds allowed existing grasses and herbaceous plants to expand and new plants to establish throughout the watershed which increased transpiration. From May 2016, the *J-RP* watershed started to recover to native prairie, while herbicide was applied to the *J-SG* watershed. For this period, the different dynamics of soil moisture for *J-RP* and *J-SG* reflected the transpiration induced soil moisture response. Suppression of transpiration by the herbicide in *J-SG* resulted in a high and less variable root zone soil moisture storage while *J-RP* experienced minimum root zone soil moisture in the late growing season corresponding to maximum leaf area of recovering vegetation.

Overland flow is an important component of the annual runoff in this study region (Qiao et al., 2017). Therefore, the antecedent soil water before and during the rainy season influences the total runoff depth for a year. In the transition phases, an apparent trend was that the root zone soil water storage more frequently approached the peak storage value, leading to potentially higher overland flow.

Application of herbicide to kill herbaceous plants in preparation of planting switchgrass is a common practice. Eliminating all vegetation by herbicide at hillslope and watershed scales always raises a great concern regarding soil erosion, especially if application is followed by large rainfall events. In our study, the largest runoff depth for a single event for *J-SG* during the herbicide period was 28.0 mm, which was three times greater than 8.9 mm in *J-RP* and 85 times higher than 0.3 mm in *J* for the same precipitation event. It is important to take the potential rainfall condition into consideration when determining the timing of herbicide application for switchgrass planting.

4.2. Increase in root zone soil moisture and runoff under restored grassland phase

In our study, the state change in root zone soil moisture storage was detected only for juniper removal but no further change was detected due to prairie restoration or switchgrass establishment. Based on the statistical result, the intercept of the linear regressions increased significantly following grassland restoration compared to the calibration phase, which suggests the juniper woodland has a much higher precipitation threshold needed to produce runoff and that conversion from juniper to herbaceous vegetation decreases the precipitation threshold for runoff generation. The increase in slope of the regression line during the transition and restored grassland phases means greater increase in runoff depth per unit increase in precipitation, suggesting a quick and steady rise of runoff in restored grasslands relative to the pre-treatment

Table 3
Statistical results of regression analyses for event-based runoff (square root transformed) between *J* and *J-RP*, and between *J* and *J-SG* during calibration phase (from October 2010 through June 2015), cut and drying phase (from July 2015 through January 2016), recovery or herbicide phase (from May 2016 through March 2017) and restored prairie or established switchgrass phase (from May 2017 through September 2018). Coefficients for slope and intercepts are presented ± SE.

Regressions*	Phases	Slope		Intercept		R^2
		Coefficient	*P values*	Coefficient	*P values*	
J vs. *J-RP*	Calibration	0.62 ± 0.02	< 0.001	0.003 ± 0.02	0.902	0.91
	Cut juniper, drying	1.27 ± 0.37	0.009	0.68 ± 0.41	0.132	0.59
	Recovery to prairie	2.82 ± 0.35	< 0.001	0.12 ± 0.15	0.425	0.74
	Restored prairie	1.19 ± 0.11	< 0.001	0.28 ± 0.11	0.013	0.79
J vs. *J-SG*	Calibration	0.90 ± 0.04	< 0.001	−0.11 ± 0.06	0.049	0.91
	Cut juniper, drying	0.77 ± 0.04	0.098	1.05 ± 0.46	0.057	0.34
	Herbicide	2.96 ± 0.64	< 0.001	0.64 ± 0.29	0.039	0.51
	Established switchgrass	1.41 ± 0.16	< 0.001	0.73 ± 0.16	< 0.001	0.77

**J*: the intact control watershed of juniper; *J-RP*: the cut watershed allowed to restore to native prairie *(J-RP); J-SG:* the cut watershed converted to switchgrass *(J-SG)*.

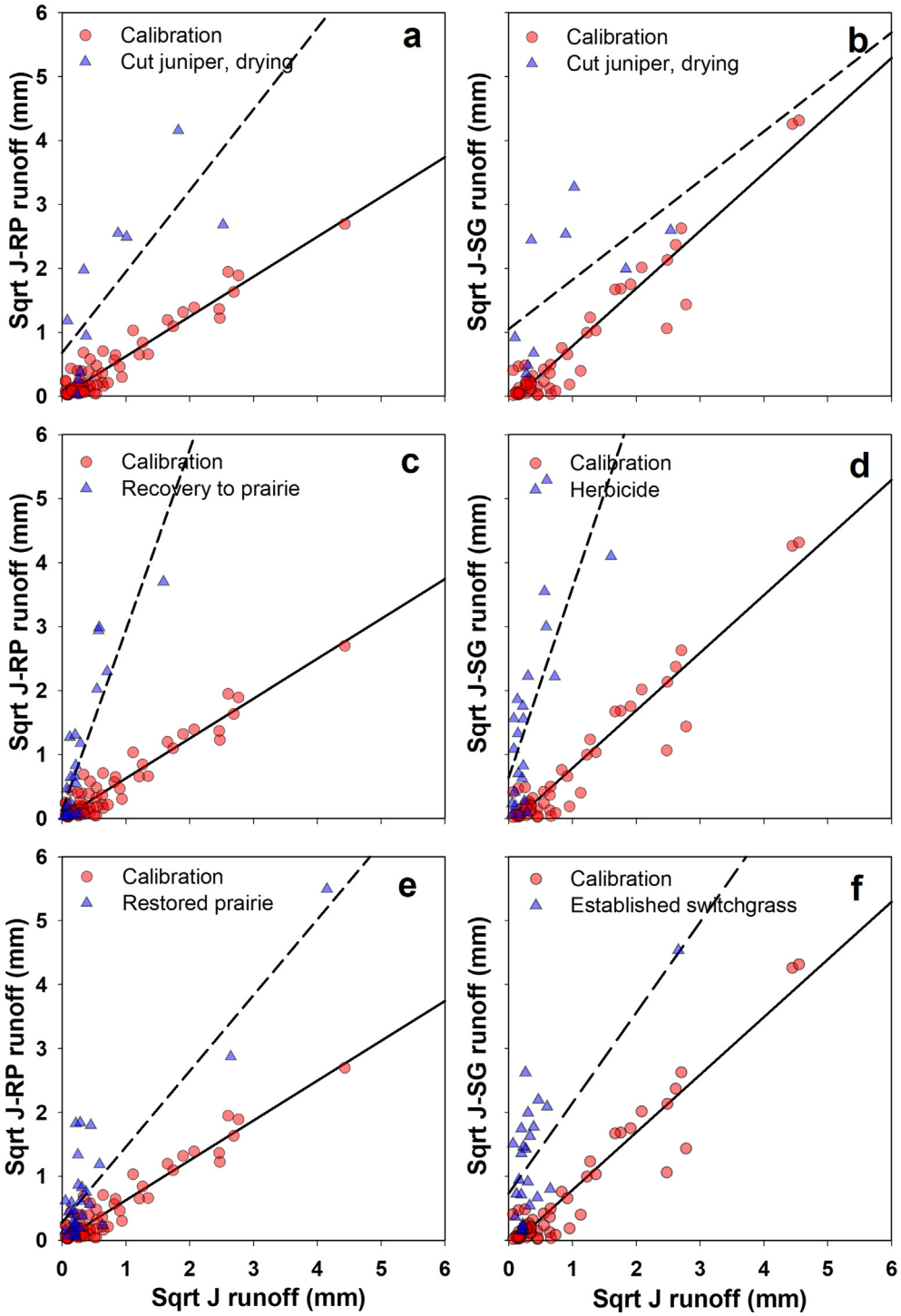


Fig. 5. Event-based linear relationship of square root transformed runoff depth between the control juniper watershed (*J*) and the treated watersheds in three phases: calibration; transition (juniper cut and drying, recovery to prairie or herbicide treated); restored grassland. The calibration phase was from October 2010 through June 2015, the juniper cut and drying phase (a, b) was from July 2015 through January 2016, the recovery to prairie phase for *J-RP* (c) and the herbicide phase for *J-SG* (d) were from May 2016 through March 2017, and the restored prairie phase for *J-RP* (e) and the established switchgrass phase for *J-SG* (f) were from May 2017 through September 2018.

phase. During the established grassland phase, the total runoff depth for restored prairie and switchgrass production system increased by 4.46 and 4.54 fold, respectively. In the switchgrass production system, the majority of aboveground biomass was removed following first frost in 2017 and 2018, leaving a site with less canopy cover during the dormant season. Even for the restored prairie, change in species composition and management approaches will likely alter the runoff regime in the future.

4.3. Juniper removal and water recovery potential

Juniper has encroached into millions of hectares in Oklahoma, Kansas, and Nebraska (McKinley 2017) and it is getting worse. However, most encroached areas have very low canopy cover and the areas with high juniper density are still relatively small (Wang et al., 2017). Given its current status, large scale or regional campaigns of juniper removal will not be effective solely for water recovery. Instead, our results show that treating heavily encroached parcels can result in the localized increase in runoff, which could be meaningful for increasing the water for retention ponds and upland reservoirs in the southern and central Great Plains. Those ponds and upland retention structures collect flow from the overland flow and intermittent streams. In most cases, juniper removal to regain space and restore soil moisture condition for enhancing grass production may be a more direct motivation

Table 4
Statistical results of the comparison of the regression line of slope and intercept between calibration phase (from October 2010 through June 2015) with cut and drying phase (from July 2015 through January 2016), recovery and herbicide phases (from May 2016 through March 2017), and restored grassland phases (from May 2017 through September 2018).

Phase Contrast	Runoff regression pair*	*P* values	
		Slope	Intercept
Calibration vs. Cut juniper, drying	*J* vs. *J-RP*	< 0.001	< 0.001
Calibration vs. Recovery to prairie	*J* vs. *J-RP*	< 0.001	0.21
Calibration vs. Restored prairie	*J* vs. *J-RP*	< 0.001	0.001
Calibration vs. Cut juniper, drying	*J* vs. *J-SG*	0.52	< 0.001
Calibration vs. Herbicide	*J* vs. *J-SG*	< 0.001	< 0.001
Calibration vs. Est. switchgrass	*J* vs. *J-SG*	< 0.001	< 0.001

for ranchers. Restoration of the runoff regime to sustain streams and refill reservoirs are added benefits.

A large swath of the Great Plains is climatically adapted for the cultivation of switchgrass. Although the planting and harvesting requirements prevent switchgrass application in many rangeland sites with rocky outcrops, our results show that switchgrass production provides an alternative land use option which could provide a hydrological function similar to restored native prairie.

5. Conclusion

Our study concludes that the paired watershed approach is an effective method to detect the impacts of vegetation manipulation on hydrological processes such as the change in rooting zone soil moisture storage and runoff dynamics to address field-scale issues on relatively flat rangeland watersheds. However, this method requires long term monitoring on the runoff and soil moisture data. Mechanical removal of juniper trees increases watershed soil moisture storage and decreases the threshold of precipitation to generate surface runoff. Converting juniper woodland to prairie resulted in a four to five fold increase in total runoff at the experimental watershed scale in the southcentral Great Plains. The hydrograph analyses suggest more extensive and delayed flow in restored prairie than that of established switchgrass. These observations and the conclusions are based on well defined, small upland watersheds in the tallgrass prairie climate transition zone in the southern Great Plains of the United States. Further work should explore whether such results apply to the mixed prairie where woody encroachment is rapidly transitioning the landscape to a woody state.

CRediT authorship contribution statement

Yu Zhong: Writing - original draft, Writing - review & editing. **Chris B. Zou:** Conceptualization, Writing - original draft, Writing - review & editing. **Adrian Saenz:** Writing - review & editing. **Elaine Stebler:** Writing - review & editing. **Gopal Kakani:** Writing - review & editing. **Rodney E. Will:** Conceptualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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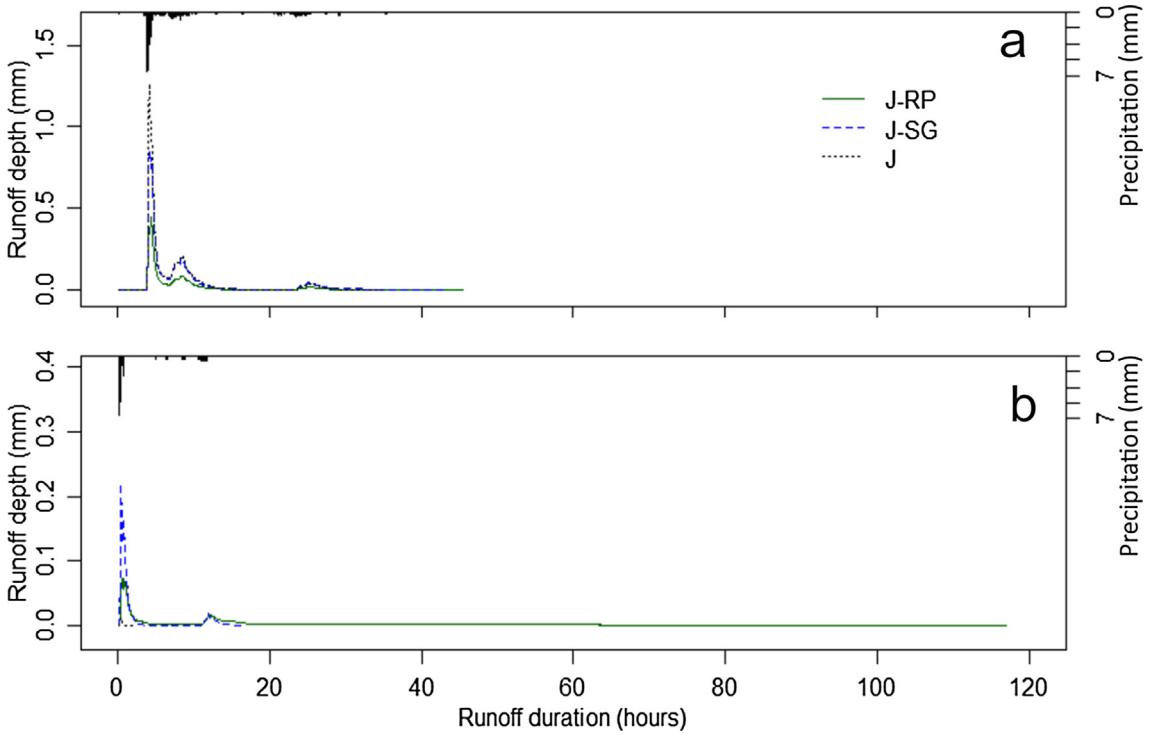


Fig. 6. Comparison of hydrograph of control watershed *J* and treated watersheds *J-RP* and *J-SG* for a storm event on May 23rd, 2015 during the calibration phase (a) and for a storm event on May 2nd, 2018 during the restored grassland phase (b).

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