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Biohydrologic effects of eastern redcedar encroachment into grassland, Oklahoma, USA*

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Abstract: Woody encroachment affects the biohydrology of rangelands worldwide and can increase evapotranspiration by increasing plant rooting depth, increasing the duration of the growing season, or by initiating a process of hydrologic recovery in formerly overgrazed landscapes. Eastern redcedar (*Juniperus virginiana*) is encroaching rapidly into rangelands in the Southern Great Plains of the USA, and beyond, including Oklahoma. However, the degree to which increasing growing season duration causes higher evapotranspiration after encroachment is not known. Here we show that increasing the duration of the growing season in north-central Oklahoma's water-limited climate from seven months (April – October) to 12 months increases modeled evapotranspiration only marginally, from 95% to 97% of precipitation. However, this increase in evapotranspiration with woody encroachment into grassland corresponded to a two-thirds reduction in deep drainage. This study's estimate of the hydrologic effects of eastern redcedar encroachment is likely to be highly conservative because it does not take into account the runoff-inducing effects of livestock grazing. Comparing simulated hydrologic fluxes in the present study to past work measuring runoff from grazinglands suggests that eastern redcedar encroachment into overgrazed rangelands is likely to increase evapotranspiration significantly. Whether or not eastern redcedar encroachment effects on evapotranspiration are discernable at the watershed scale will depend on the extent of encroachment throughout the watershed. Further research is necessary to quantify how the hydrologic effects of eastern redcedar encroachment vary due to climatic gradient.

Key words: Hydrus; Landsat; evapotranspiration; groundwater recharge; rangeland

Introduction

Two effects of eastern redcedar encroachment are to reduce the grazing rate—commonly from a high antecedent rate—to zero, and to increase the length of the growing season (Fig. 1). The effects of grazing rate on runoff and the water balance are well known. Higher grazing rates lower infiltration rates and as a result route a higher proportion of precipitation to runoff (Gifford & Hawkins 1978; Trimble & Mendel 1995; Wine et al. 2012). However, less is known about eastern redcedar's effect of transpiring for significantly more of the year than the grasses that it replaces. In Payne County, Oklahoma upland soils commonly average 80-90 cm deep and are underlain by saprolite (Soil Conservation Service 1987, Wine & Zou 2012). Both grasses and eastern redcedar have been observed to deplete water to well in excess of these depths at locations with deep soils (Berg & Sims 1984; Eggemeyer et al. 2009). Given the aforementioned soil depths, both grasses and trees are likely to extract water from the entire soil profile under these conditions. The major distinction lies in that the grasses senesce by November and remain dormant through March, whereas eastern redcedar can transpire on any day when temperatures are above freezing, even if the ground is frozen (Eggemeyer et al. 2006). The goal of this paper is to elucidate the effects of eastern redcedar's longer growing season on evapotranspiration in north-central Oklahoma.

Material and methods

Representative geology of Payne County, Oklahoma is early Permian shale and sandstone. Moderately deep soils of the Grainola–Lucien and Stephenville–Darnell complexes are common (Soil Conservation Service 1987). Grainola soils are fine, mixed, active, thermic Udertic Haplustalfs; Lucien are loamy, mixed, superactive, thermic, shallow Udic Haplustolls; Stephenville are fine-loamy, siliceous, active, thermic Ultic Haplustalfs; and Darnell are loamy siliceous, active, thermic, shallow Udic Haplustepts. The climate is continental, and annual precipitation is highly variable (median annual precipitation, 1895–2010 = 831 mm; range = 424–1571). The topography slopes gently.

We ran two Hydrus 1-D (Šimůnek & van Genuchten 2008; Šimůnek et al. 2008) simulations over a 13-year period from 2000–2012 using climate data (precipitation, wind speed, air temperature, dew point temperature, atmospheric pressure, and solar radiation) from the Oklahoma Mesonet

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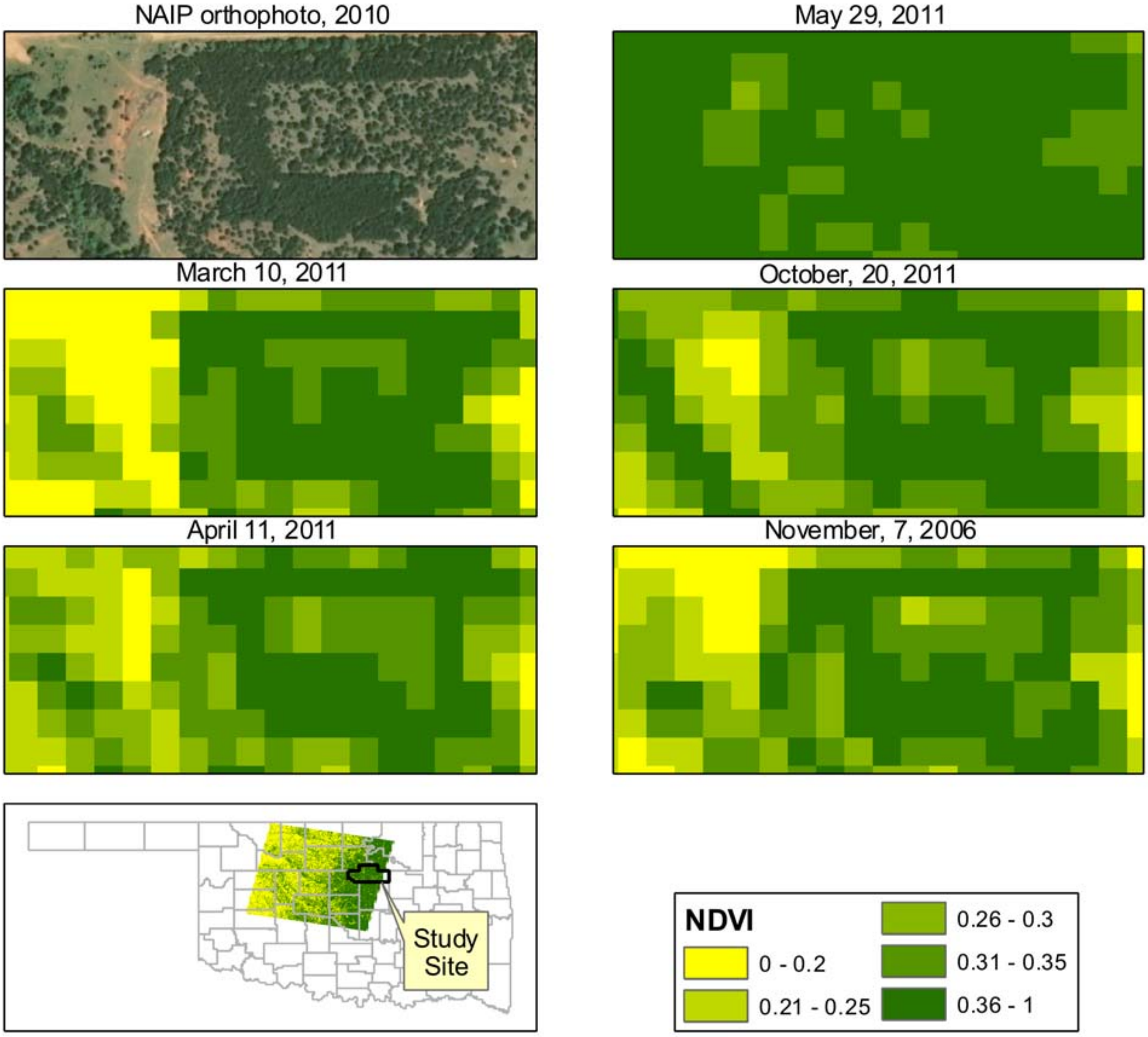

Fig. 1. The National Agriculture Improvement Program (NAIP) orthophoto shows eastern redcedar woodland and adjacent grassland at the Cross Timbers Experimental Range, Payne County, Oklahoma. Normalized Difference Vegetation Index (NDVI) was computed from Landsat 5 imagery and indicates that grasses begin to green in April and senesce by November.

(Brock et al. 1995). These data are extensively quality controlled through field visits, automatic quality assurance procedures, and manual inspection of data (Shafer et al. 2000). From these data we calculated reference evapotranspiration (Allen 2005) using Model Builder in ArcGIS 10.1. The Marena station was used primarily, but where data from this station were missing gaps were filled with data from the nearby Stillwater station. Both stations are located in Payne County, Oklahoma. The model used a soil profile 90 cm deep with van Genuchten-Mualem parameters for a clay loam. The upper boundary condition allowed runoff when the soil's infiltration capacity was exceeded and the lower boundary condition was free drainage. For the grass simulation Feddes' root water uptake parameters for a grass were used, whereas for eastern redcedar parameters appropriate for a juniper were used (Feddes et al. 1974; Gutierrez-Jurado et al. 2006). Duration of transpiration and root water uptake parameters were varied between the two model runs. The grass model run attempted to mimic grassland that started to transpire in April and ceased to transpire at the end of October. In contrast, the next model run attempted to model two of eastern redcedar's salient features—a continuous propensity to transpire throughout all months of the year and the ability to extract water from the soil even at high suctions due to its strategy of drought tolerance (Bihmidine et al. 2010). Precipitation interception was not explicitly modeled for either run in the present study because it is not yet well known for eastern redcedar. However, the reference evapotranspiration used as a forcing variable in the model does take into account precipitation interception, in addition to soil water evaporation and transpiration. One-tailed paired t-tests were used to assess differences between treatments.

Results and discussion

Precipitation averaged 849 mm and ranged from a low of 585 mm in 2011 to a high of 1370 mm in 2007 (Table 1, Fig. 1). Reference evapotranspiration varied correspondingly, averaging 1,785 mm, and ranging from a low of 1,507 mm in 2007 to a high of 2,209 mm in 2011. Thus, over the course of the study reference evapotranspiration exceeded precipitation by approximately

Table 1. Reference evapotranspiration (ETr), precipitation (PCP), runoff, evapotranspiration, and recharge below 90 cm for a clay loam soil in Payne County, Oklahoma. Runoff, recharge, and evapotranspiration were simulated by Hydrus 1D. Simulations uncovered significantly higher recharge under grass than under eastern redcedar.

			Grass						Juniper					
	Etr	PCP	Runoff		ET		Recharge		Runoff		ET		Recharge	
Year	mm		mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
2000	1,745	900	0	0	783	87	0	0	0	0	783	87	0	0
2001	1,730	709	0	0	778	110	12	2	0	0	806	114	0	0
2002	1,606	969	0	0	871	90	17	2	0	0	895	92	0	0
2003	1,723	682	4	1	727	107	8	1	3	0	720	105	0	0
2004	1,563	961	0	0	826	86	9	1	0	0	843	88	0	0
2005	1,715	880	35	4	892	101	81	9	33	4	970	110	35	4
2006	2,129	621	0	0	588	95	35	6	0	0	557	90	1	0
2007	1,507	1,370	22	2	904	66	0	0	22	2	956	70	0	0
2008	1,755	956	25	3	925	97	134	14	23	2	995	104	109	11
2009	1,742	989	0	0	896	91	65	7	0	0	944	95	1	0
2010	1,695	812	20	2	852	105	20	3	19	2	840	103	1	0
2011	2,209	585	0	0	547	93	11	2	0	0	516	88	0	0
2012	2,090	599	0	0	637	106	0	0	0	0	660	110	0	0
Mean	1,785	849	8	1	787	95	30	3	8	1	806	97	11	1

a factor of two, but by nearly a factor of four in 2011. As a result of the high evaporative demand, simulated actual evapotranspiration from grass averaged 787 mm, 95% of precipitation and simulated eastern redcedar evapotranspiration averaged 798 mm, 97% of precipitation. Evapotranspiration commonly exceeded annual precipitation as soil water stored during wet years (e.g., 2000) was transpired during dry years (e.g., 2001). Interestingly, evapotranspiration from grass sometimes exceeded eastern redcedar evapotranspiration. This occurred after eastern redcedar drew down soil water storage during one year (e.g., 2009) and thereafter had less stored water available to transpire than the grass, which had been dormant. Runoff was essentially the same for both treatments because the same soil hydraulic parameters were used averaging 8 mm and ranging from none in most years to 35 mm in 2005 in response to a 10 cm storm on June 16, 2005. However, deep recharge below 90 cm was significantly higher under grass than under eastern redcedar ($p = 0.002$). Recharge averaged 30 mm under grass, but only 11 mm under eastern redcedar. No recharge occurred during years (e.g., 2012) preceded by dry years (e.g., 2011) for either treatment. Conversely in 2008, the largest recharge event of over 100 mm occurred for both treatments after unusually high precipitation in 2007 followed by above average precipitation in 2008. In 2009, recharge under grass exceeded that under eastern redcedar by the greatest magnitude (64 mm) due to above average, though not exceptionally high precipitation, in 2008 and 2009. In contrast, similar to past work (Pekárová et al. 2009), recharge rates under eastern redcedar and grass were more similar following both exceptionally dry and exceptionally wet years.

While the present study adopted a simple methodology to elucidate the effects of growing season duration on evapotranspiration, it provides a measure of confidence to note that deep drainage estimated in this study under grass of 30 mm is comparable to long-term measured groundwater discharge from a nearby mixed land-use watershed, also of 30 mm (Wine & Zou 2012). The present study may over-estimate grass evapotranspiration somewhat since no attempt is made to account for early senescence during droughts. Similarly, eastern redcedar evapotranspiration may be underestimated because the possibility that its roots might penetrate into saprolite or cracks in the underlying bedrock is not accounted for. Furthermore, eastern redcedar evapotranspiration simulated in this study could be lower than might be expected of eastern redcedar encroachment into a riparian or lowland area where its roots might be able to access a water table.

The present study aimed to assess the effects of growing season duration on evapotranspiration and in doing so controlled for infiltration rate by using the same representative hydraulic conductivity for clay loam in both simulations. In reality, in the region of the study area, grazing rates can be high. Grazing in this region commonly compacts the upper 10 cm of soil, reducing the infiltration rate by an order of magnitude (Daniel et al. 2002). As a result 99 mm of runoff was measured from heavily grazed, degraded field-scale experimental watersheds in Oklahoma or about 12% of precipitation (Smith et al. 1992). If we assume that eastern redcedar encroachment into such a heavily grazed watershed following the results of the present study ultimately resulted in 97% of precipitation evaporating, then encroachment into the aforementioned overgrazed watershed would likely increase evapotranspiration by 74 mm (or nine percentage points of precipitation), a significant increase in consumptive water use. Thus, while eastern redcedar encroachment into a well-managed upland site in north-central Oklahoma may increase evapotranspiration only slightly, encroachment into an overgrazed, degraded site, is likely to increase evapotranspiration significantly. Similarly the effects of eastern redcedar removal on evapotranspiration must depend on the grazing rate following removal. However, whether or not any increases in evapotranspiration are discernable at the watershed scale will also depend on the proportion of the watershed affected by encroachment. The present study concurs with past work in suggesting that while woody encroachment can increase evapotranspiration significantly, those increases are strongly dependent on the degree to which the site was degraded prior to woody encroachment (Wilcox et al. 2008).

While the present study was restricted to long-term dynamics at a single location the potential for woody encroachment to increase evapotranspiration can be predicted based on annual precipitation and evaporative demand (Zhang et al. 2001). Thus, the hydrological effects of eastern redcedar are likely to vary both in space and in time across Oklahoma because of this state's strong climatic gradient. In north-central Oklahoma these climatic forcings have caused annual streamflow duration to vary from 9 days of streamflow during a dry year to 366 days of streamflow during a moist leap year (Wine & Zou 2012). In addition to this temporal variation, annual precipitation decreases and consequently evaporative demand increases moving in a roughly westerly direction across Oklahoma. Runoff varies correspondingly, averaging 7 mm on well-managed rangelands in western Oklahoma, but 143 mm in north-central Oklahoma (Wine & Zou 2012; Wine et al. 2012). In western Oklahoma, not only is runoff minimal from well-managed rangelands, but deep drainage from uplands is likely negligible as well ($\leq$ 0.1 mm yr^{-1}), based on nearby studies out of northern Texas (Scanlon & Goldsmith 1997). Since the present study examines the hydrologic effects of woody encroachment at a single location, it is necessary to consider the effects of climatic gradients when applying the results of this study to larger areas. Finally, further research is necessary to determine how eastern redcedar encroachment affects partitioning between evaporation (Budagovskyi & Novák 2011b) and transpiration (Budagovskyi & Novák 2011a).

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