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Understanding the effects of pasture type and stocking rate on the hydrology of the Southern Great Plains

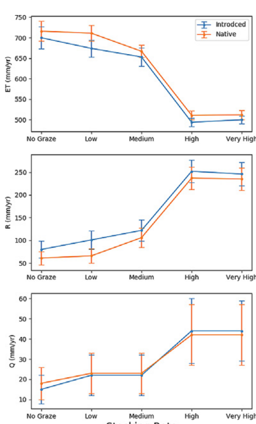
R. Niraula [a,*], A. Saleh [a], N. Bhattarai [b], R. Bajgain [c], N. Kannan [a], E. Osei [d], P. Gowda [e], J. Neel [e], X. Xiao [c], J. Basara [f,g]

[a] Texas Institute for Applied Environmental Research (TIAER), Tarleton State University, Stephenville, TX, USA
[b] School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, USA
[c] Department of Microbiology and Plant Biology, University of Oklahoma, Norman, OK, USA
[d] Agricultural and Consumer Sciences, Tarleton State University, Stephenville, TX, USA
[e] Forage and Livestock Production Research Unit, USDA-ARS Grazinglands Research Laboratory, El Reno, OK, USA
[f] School of Meteorology, University of Oklahoma, Norman, OK, USA
[g] School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, OK, USA

HIGHLIGHTS

- APEX assessed the hydrological impacts of pasture types and stocking rates in SGP.
- Monthly ET and biomass from APEX were comparable with observed data.
- Introduced pasture yielded higher water yield and lower ET than native pasture.
- Grazing has the potential to alter the hydrological balance in the SGP.
- Future pasture management plans should consider these hydrological impacts in SGP.

GRAPHICAL ABSTRACT



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ABSTRACT

Grassland is one of the major biomes in the United States (US) and the world. In the US, the majority of grasslands are concentrated in the Great Plains and has undergone through significant interventions or management changes over the last few decades. A key economy-driven intervention in the Southern Great Plains (SGP) include the introduction of new forage species and conversion of native grassland to introduced pasture to increase productivity and its nutritive value for improved cattle production. Since water is one of the fundamental resources needed to sustain grassland productivity, it is important to understand how such pasture conversion and prevailing cattle grazing practices affect water balance and biomass production in a given pasture system. In this study, the Nutrient Tracking Tool (NTT) with its core APEX (Agricultural Policy Environmental eXtender) model was used to assess the hydrological impacts of the pasture introduction, i.e., native pasture (little bluestem, *Schizachyrium halapense*) vs. introduced pasture (old world bluestem, *Bothriochloa caucasica*), and the stocking rate in the SGP. Monthly evapotranspiration (ET) and biomass estimates from NTT compared well with observed data

* Corresponding author at: Lynker, 3002 Bluff Street, Suite 101, Boulder, CO 80301, USA.
E-mail address: rewatin@gmail.com (R. Niraula).

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APEX
NTT
Southern Great Plains

at two USDA-ARS experimental pastures (native and introduced) near El Reno, Oklahoma, for the years 2015 and 2016. Simulated long-term average annual hydrologic fluxes (i.e., ET, runoff, and groundwater recharge) from the introduced pasture were slightly lower than the observed data but not significantly different than those from the native pasture under the current management conditions. NTT predicted higher water yield (runoff and recharge) and significantly lower ET for the introduced pasture than the native pasture. Results suggest that grazing has the potential to alter the hydrological balance in the SGP. For example, the increase in stocking rate within the carrying capacity of the farm decreases ET and increases runoff and groundwater recharge for both pastures. Comparison of estimated biomass production between native and introduced pastures indicated that introduced pastures are more efficient in using the available water and thus produce a higher forage biomass per unit of water in the SGP. This study highlighted the potential significance of considering hydrological and other biophysical impacts of new forage introduction and stocking rate changes for the sustainable management of grazing and pasture systems in the SGP.

1. Introduction

Grasslands are among the major ecosystems in the world, occupying approximately 40% of the earth's terrestrial surface (Blair et al., 2014). In the United States (US), grassland is considered a key land cover type, which accounts for a significant amount of US's grazing lands (Sampson and Knopf, 1994). A majority of US grasslands are concentrated in the Great Plains, where native prairies and introduced pastures serve as a major forage source for beef cattle production, a major economic activity in the region. Management practices on these pasture systems are diverse (e.g., burning, grazing, baling, fertilizing), complex (e.g., a mixture of management practices such as grazing and baling, different duration and timing), and can vary with space, time, and available resources. For example, prescribed burning is a recommended management practice to recycle plant nutrients, remove senesced vegetation, control weeds, and inhibit encroachment from invasive species (Brockway et al., 2002; Reinhart et al., 2016; Twidwell et al., 2013; Valkó et al., 2014, Zhou et al., 2017). However, it could significantly alter carbon balance, reduce water quality, and later biodiversity (Harper et al., 2018). In addition, excessive grazing can remove aboveground biomass, reduce canopy coverage, and negatively affect important plant biophysical activities, such as vegetation photosynthesis and evapotranspiration (ET) (Zhou et al., 2017).

Understanding the spatiotemporal dynamics of the water cycle in grassland ecosystems under different managements has a direct implication on both climatic and economic processes across the US and the world (Brunsell et al., 2008). Water is one of the fundamental resources that drive these grassland ecosystems in this region. Evapotranspiration (ET), in particular, plays a critical role in the hydrologic cycle and represents the process that links both the energy and water cycles (Wang and Dickinson, 2012). In a semi-arid environment, ET is a major pathway of water loss and can account for up to 95% of the precipitation input (Huxman et al., 2005; Wang et al., 2012; Wang et al., 2013). In the US Great Plains, native grasslands are often managed by introducing new forage species with the aim of enhancing their biomass productivity and nutritive value and cattle productivity. Non-native plant introduction may alter the seasonal water availability because of differences in their phenology and consequent water use patterns. It also introduces changes in surface and soil characteristics altering the surface and subsurface water flows, infiltration rates, and water residence times (Catford, 2017). Although non-native plants are often assumed to use more water than co-occurring natives, they generally have faster growth rates (van Kleunen et al., 2010), higher rates of photosynthesis and higher rates of leaf-level water use (Leishman et al., 2007; Cavaleri and Sack, 2010). Other studies (e.g., Blicker et al., 2003; Wise et al., 2011) have suggested that water use efficiency of introduced species are similar or more than that of native species. The effect of introduced species on water yield over time, however, depends greatly on the species involved and site-specific conditions (Dye and Jarmain, 2004; Doody and Benyon, 2011; Doody et al., 2011; Cavaleri et al., 2014). This suggests that the hydrological impacts of new forage species introduction in a given grassland should be studied at a local to regional scales. Unfortunately, our current knowledge on the water implications of species introduction in the semi-arid and sub-humid regions such as the US Southern Great Plains (SGP) that covers a significant proportion of US grasslands is scant.

Both native and introduced grasslands are common in the SGP, however, their role in regional energy and water exchange processes has not been adequately studied in the past. Such information is critical for the sustainable management of grassland and grazing systems in this region. In this study, we aim to understand how the conversion of native to introduced pasture could affect the hydrologic balance and biomass production in the SGP. Specifically, we assessed the effect of native (little bluestem) and introduced (old world bluestem) grassland ecosystems and grazing on the hydrology of the SGP using Nutrient Tracking Tool (NTT, Saleh et al., 2011). NTT with its core Agricultural Policy Environmental eXtender (APEX, Williams et al., 2015) was initially developed to simulate hydrological balance, water quality and crop yield (Saleh et al. 2011; EPRI, 2011; Moriasi et al., 2016; Saleh et al., 2018). This study aims to apply NTT in a calibration/validation mode to answer scientific research questions, such as what is the hydrological impact of grazing and stocking rate in the SGP? and what are the water implications of introducing new pasture systems in the SGP? Through the application of NTT tool, we aim to provide vital information to pasture and water resource managers for the sustainable management of grassland ecosystem in the SGP.

2. Methodology

2.1. Site description

The study site (Fig. 1) consists of two pasture fields in El Reno, OK that are managed by the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) Grazing Lands Research Laboratory (GRL). The first field or Pasture 11 (35.54679°N, 98.04529°W, 435 m above sea level) covers an introduced warm-season pasture farm planted with old world bluestem (*Bothriochloa caucasica* C. E. Hubb.) in the year 1989 (Coleman and Forbes, 1998). The second field or Pasture 13 (35.54865°N, 98.03759°W, 435 m above sea level) is the control pasture field that covers native grass species (Fischer et al., 2012); i.e., little

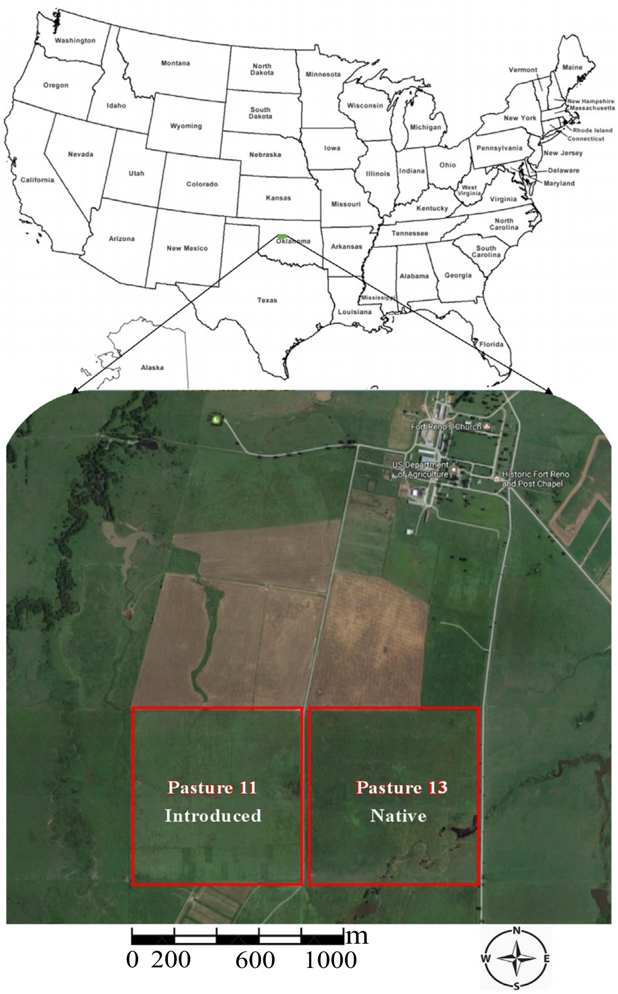

Fig. 1. Location area map of study plots.

bluestem [*Schizachyrium halapense* (Michx.) Nash.] and big bluestem (*Andropogon gerardi* Vitman).

The two study pasture fields are very similar in size and other site characteristics (Table 1). For example, soil type in both fields is classified as Norge silt loam (Fine-silty, mixed, active, thermic Udic Paleustolls) with a depth of impeding layer greater than 1 m and high water holding capacity (Fischer et al., 2012). Both pasture fields are relatively flat with an average slope of <3%. Under current management conditions (Table 1), the pasture fields are planted, grazed, and burned. In addition, the introduced pasture is fertilized and hayed occasionally.

Both fields fall under the temperate continental climate (warm temperate fully humid with hot summer). Based on PRISM gridded climate data (http://prism.oregonstate.edu), the 28-year (1989–2016) annual average precipitation is ~ 793 mm, with no clear increasing or decreasing trend (Fig. 2). The average maximum and minimum temperature in the study sites are 21.5 °C and 8.9 °C, respectively. Updated PRISM database is incorporated within the Nutrient Tracking Tool (NTT; Saleh et al., 2011) framework to be used for APEX (Agricultural Policy Environmental eXtender; Williams et al., 2015; Gassman et al., 2010) simulation, as discussed in Section 2.2.

Table 1
Properties of study pasture fields.

Properties	Pasture 11	Pasture 13
Grass type	Introduced	Native
Dominant species	Old world bluestem	Little/Big bluestem
Area	~ 64 ha	~ 64 ha
Major soil type	Norge silt loam, 1–3% slopes	Norge silt loam, 1–3% slopes
Grazing	Yes	Yes
Fertilizer	Yes	No
Burn	Yes	Yes
Hayed	Yes	No

2.2. Model/Tool description

The Nutrient Tracking Tool (NTT, Saleh et al., 2011) (http://ntt-re.tiaer.tarleton.edu/) is a user-friendly, web-based computer program developed by the Texas Institute of Applied Environmental Research (TIAER) at Tarleton State University in collaboration with USDA- Natural Resources Conservation Service. NTT is a web-based tool designed for preparing the inputs for the APEX model, and running APEX simulation, and scenario analysis. The tool estimates hydrologic fluxes (viz. ET, runoff, groundwater recharge) as well as nutrients (nitrogen and phosphorus) and sediment losses from fields managed under a variety of cropping patterns and management practices through its user-friendly linkage to the APEX. The NTT provides users (viz. farmers, government officials, and researchers) with a fast and efficient method of estimating nitrogen and phosphorus credits for water quality trading, as well as other water quality, water quantity, and farm production impacts associated with various conservation practices.

The APEX model operates at a daily time scale and is designed for use in whole farm/small watershed management systems, though the farm may be subdivided into fields, soil types, landscape positions, or any other desirable configuration. To prepare APEX input to simulate a particular scenario, there are numerous data input and parameter settings required to describe field characteristics, daily weather, soils, and crop management practices (Williams et al., 2015).

With NTT interface, users can select the study area/plot which will be automatically linked with the STATSGO soil database, PRISM weather data, and the options for different crop types and management practices suitable for the study region.

The individual field simulation component of APEX is taken from the Environmental Policy Integrated Climate (EPIC) model, which was developed in the early 1980s to assess the effect of erosion on crop productivity (Williams et al., 1984). The major components in EPIC are weather simulation, hydrology, erosion, sedimentation, nutrient cycling, pesticide fate, crop growth, soil temperature, tillage, economics, and plant environment control (Sharpley and Williams, 1990).

The APEX model was developed to extend the EPIC model capabilities in whole farms and small watersheds (Williams et al., 2015). In addition to the EPIC functions, APEX has components for routing water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet. APEX also has groundwater and reservoir components. APEX has its own databases for generating weather data, soils, crops, tillage, fertilizer, and pesticides (Williams et al., 2015). In short, APEX is a hydrologic and water quality model developed for evaluating the effect of agricultural production management practices on the environment (Williams et al., 2015) and has been used extensively for modeling hydrology, water quality and biomass/crop yield across the US at a local to national scale within (Saleh et al. 2011; EPRI, 2011; Moriasi et al., 2016; Saleh et al., 2018) and outside (Duriancik et al., 2008; Richardson et al., 2008; Gassman et al., 2010; Cavero et al., 2012; Plotkin et al., 2013; Senaviratne et al., 2013 Baffaut et al.,

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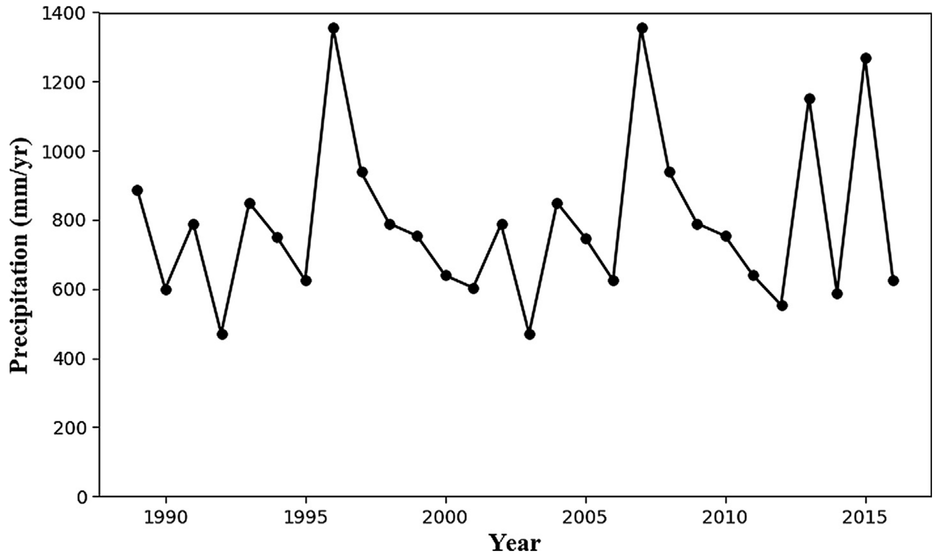

Fig. 2. Annual precipitation from PRISM in the study sites from 1989 to 2016.

2017; Nelson et al., 2017; Bhandari et al., 2017; Van Liew et al., 2017; Nelson et al., 2018) the NTT framework.

2.3. Description of measured data (ET and biomass)

2.3.1. Eddy covariance measurements

The major weather parameters or fluxes measured and used in this study include solar radiation, precipitation, maximum temperature, minimum temperature, and ET. While the first four parameters/fluxes were used as model inputs, ET was used for validation and further analysis to study the hydrologic impacts of new species introduction and stocking rate. The eddy covariance (EC) measurement system at the study plots consisted of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA) and an open path infrared gas analyzer (LI-7500, LI-COR Inc., Lincoln, NE, USA). The sensors were mounted at 2.5 m above the ground and the system was set up at the center of the field facing south, towards the prevalent wind direction. The fetch area is about 300 m in all directions. Flux data were collected at 10 Hz frequency (10 samples/sec) to get a 30-minute interval fluxes data. The EddyPro processing software (LI-COR Inc., Lincoln, NE, USA) was then used to process the raw data. The software employed correction factors for coordinate alignment, temperature due to humidity influence, compensation of density fluctuations in infrared gas analyzer using Webb–Pearman–Leuning (WPL) to make necessary corrections in the high frequency data. Quality flags were applied for screening erroneous data. The data outside ± 3.5 standard deviation range from a 14-day running mean window were identified as outliers and were excluded from the analysis.

The R package "REddyProc" based on the online tool developed at the Max Planck Institute for Biogeochemistry (Moffat et al., 2007) was utilized for gap filling of missing fluxes that either failed quality screening or were deemed unreliable due to sensor malfunction. The average value of measurements immediate before and after the gap was used to fill 30-minutes gaps. Two-hour or fewer gaps were linearly interpolated. Mean diurnal variation, look up tables, and regressions techniques were used to fill the larger gaps either in isolation or in combination based on the requirements, as described in previous studies (Wilson and Baldocchi, 2001; Falge et al., 2001; Hui et al., 2004; Moffat et al., 2007). More information about the EC instruments and measurements can be found in Bajgain et al. (2018) and Wang et al. (2019).

2.3.1.1. Vegetation measurements. Aboveground biomass was determined by destructive sampling from 0.5 m^2 quadrats with three replicates at each site. The fresh samples were oven dried at 70 °C for 72 hours and total dry weight was measured by weighing the oven-dried samples. Readers are referred to Bajgain et al. (2018) for additional details on how these measurements were conducted. The monthly biomass data were used for model validation and further analysis.

2.4. Model calibration and validation

In this study, we selected the Hargreaves-Samani (Hargreaves and Samani, 1985) based potential ET module in APEX to estimate actual ET, as recommended by Saleh et al. (2018). The model was manually calibrated using the measured ET in the native pasture (Pasture 13) for the years 2015–2016 and then validated against the measured ET over the introduced pasture for the years 2015 and 2016. No further parameter was calibrated for simulating and validating biomass. Scatter plots and statistics, such as Percent Bias (PBIAS, Eq. (1)), Nash-Sutcliffe Efficiency (NSE, Eq. (2)), and Coefficient of determination (R^2, Eq. (3)) were used for the evaluation APEX model at a monthly scale.

$$\mathrm{PBIAS} = \frac{\left(Y_i^{\mathrm{sim}} - Y_i^{\mathrm{obs}}\right)}{Y_i^{\mathrm{obs}}} * 100 \tag{1}$$

$$\mathrm{NSE} = \frac{\sum_{i=1}^{n}\left(Y_i^{\mathrm{obs}} - Y_i^{\mathrm{sim}}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{\mathrm{obs}} - Y^{\mathrm{mean}}\right)^2}, \tag{2}$$

$$R^2 = \frac{\sum_{i=1}^{n}\left[\left(Y_i^{\mathrm{obs}} - Y^{\mathrm{mean}}\right)\left(Y_i^{\mathrm{sim}} - Y_s^{\mathrm{mean}}\right)\right]^2}{\sum_{i=1}^{n}\left(Y_i^{\mathrm{obs}} - Y^{\mathrm{mean}}\right)^2 \sum_{i=1}^{n}\left(Y_i^{\mathrm{sim}} - Y_s^{\mathrm{mean}}\right)^2}. \tag{3}$$

where Y_i^{sim} is the model-simulated value, Y_i^{obs} is the ith observation, Y^{mean} and Y_s^{mean} are the means of the observed and simulated data, respectively, and n is the total number of observations. More detailed descriptions of these evaluation criteria can be found in Moriasi et al. (2007).

2.5. Long-term ET simulation and hydrological impact analysis under different scenarios

We initially make use of a remotely sensed ET product and obtained monthly ET values for both pasture fields from a newly developed global 1 km monthly ET products based on the operational simplified surface energy balance (SSEBop) (Senay et al. 2013). The monthly SSEBo ET products are available from USGS (https://earlywarning.usgs.gov/fews/datadownloads; last accessed July 6, 2018) and use MODIS land surface temperature products (Wan et al. 2015) and the global land data assimilation system (GLDAS) reanalysis data (Rodell et al., 2014). The model uses land surface temperature to derive ET at daily scale by linearly interpolating ET values from hypothetically parametrized dry and wet temperature for each pixel within an image (Senay et al., 2013). The model has been widely validated across multiple biomes and climates in the US (Singh et al., 2013; Velpuri et al., 2013; Senay et al., 2016; Senay et al., 2017).

The locally calibrated and validated APEX model was then used to simulate monthly and annual ET and other hydrological fluxes (surface runoff, Q, and groundwater recharge, R) from the native and introduced pasture fields for the period of 28 years (1989–2016). To study the effect of the introduced pasture on the hydrology (i.e., ET, Q, and R) of SGP, the inter annual variations in the hydrological fluxes from native and introduced pasture field were evaluated. Specifically, the effect of stocking rate on the hydrology was evaluated by considering four scenarios of stocking rate (Table 2), which were based on the 2 years (2015–2016) field collected grazing data for native and introduced pasture fields.

The APEX model was simulated for a period of 28 years (1989–2016). Introduced pasture has approximately twice the carrying capacity compared to native pasture because of its higher forage biomass potential. Thus, the average ('Medium') stocking rate for native and introduced pasture were considered to be 0.5 head/ha and 1 head/ha, respectively. The stocking rate scenarios (Table 2) were created based on the field data available for the study period. The grazing animals are cow/calf pairs, which were allowed to graze for the entire day period during each day of the growing season.

3. Results and discussions

3.1. Remote sensing approach to estimate field scale ET

The initial validation of this product using EC data showed significant overestimation (19% for native species and 38% for introduced species), similar to those reported in previous studies (Bhattarai et al., 2016; Bhattarai et al., 2017; Wagle et al. 2017). Limitations of remote sensing based ET at field scale include uncertainties associated with coarse resolution weather inputs (12.5 to 25 km) and remotely sensed products itself to characterize ET at a local scale. No other remote sensing ET product at 1 km or higher spatial resolution for a long-term analysis, such as the case in our study (i.e., covering before 2000 and after the year 2015), is currently available. Hence, we fully relied upon the locally calibrated APEX model, which appears to be more applicable for analyzing the long-term hydrological impacts of pasture types and stocking rate in our study sites.

Table 2
Stocking rate scenarios for native and introduced pastures.

Scenarios	Stocking rate class	Stocking rate (Cow/calf/ha)	
		Native	Introduced
1	Low	0.25	0.5
2	Medium	0.5	1
3	High	1	2
4	Very High	2	4

3.2. ET calibration/validation

After calibration for the 2 years period (2015–2016), NTT/APEX model was able to simulate the ET within 1% of the measured ET (Table 3) for the native pasture. Both the NSE and R^2 values during model calibration were 0.98 for native pastures (Fig. 3 and Table 3). The model performed equally well for the validation pasture (introduced) with the PBIAS within 1% and NSE and R^2 greater than 0.95. The 2-year average annual ET was higher for native pasture (Pasture 13; ET = 802 mm/year) compared to that from the introduced pasture (ET = 711 mm/year; Pasture 11).

3.3. Biomass calibration/validation

APEX was able to simulate biomass with good accuracies for both native and introduced pastures within 2% of the measured biomass for the 2-year period (2015–2016) (Fig. 4). Model estimated biomass explained 74% variability in measured biomass and the NSE values were over 0.6 for both pastures. Overall, these results suggest APEX applicability to simulate biomass on different pasture systems.

3.4. Long term forage biomass potential

The forage biomass potential for introduced pasture (7.7 ± 1.9 tons/ha) was found to be significantly higher ($P < 0.05$) than that of the native pasture (3.5 ± 0.4 tons/ha), which is similar to those reported in other studies (Sanderson et al., 1999; Duch-Carvallo, 2005; Philipp et al., 2007). The old world bluestems (i.e., introduced species) in pasture 11 is a warm-season perennial grass that was brought to the US in the early 1999s from southern Europe and Asia for forage grass and as erosion control (McCoy et al., 1992; MDC, 2010). This grass is capable of producing high quality forage with limited or no irrigation (Philipp et al., 2005; Allen et al., 2012) and gained popularity in the Southern Great Plains because of its high biomass production and nutritional quality compared with other forage grasses (Sanderson et al., 1999; Duch-Carvallo, 2005; Philipp et al., 2007). This value is well within the forage biomass potential of old bluestem in the central Oklahoma region (i.e., 5–12 tons/ha), reported by the Oklahoma Cooperative Extension Services (OCES 2018). Coyne and Bradford (1985) suggested that the old world bluestem stands can produce up to four times the forage of well-managed native rangeland. The high productivity of introduced pasture could be attributed to fertilization and water efficiency.

3.5. Effect of grassland type on the hydrological fluxes

Under the current management conditions, the average annual measured ET for the 2015–2016 period was found to be comparatively lower in the introduced pasture (~−10%) than that over native pasture (Table 4). This was well captured by the APEX. APEX is designed to capture the difference in the growth and development of grass type through several crop factors including leaf area index, maturity time, maximum crop height and root depth, nutrient uptake, biomass-energy ratio, stomatal conductance, optimal temperature, and heat units required for germination. When compared over the 28 years period of simulation, under current management conditions, the mean annual ET from the native pasture was not statistically different ($P > 0.05$) than those from the introduced pasture (Fig. 5). But it should be noted that this value was influenced by management conditions (viz. stocking rate). Under

Table 3
Evaluation statistics of simulated ET during model calibration and validation.

Pasture	Calibration/validation year	Measured (mm/yr)	Simulated (mm/yr)	R^2	NSE	PBIAS
Native	calibration (2015–2016)	802	797	0.98	0.98	<1%
Introduced	validation (2015–2016)	711	718	0.96	0.95	<-1%

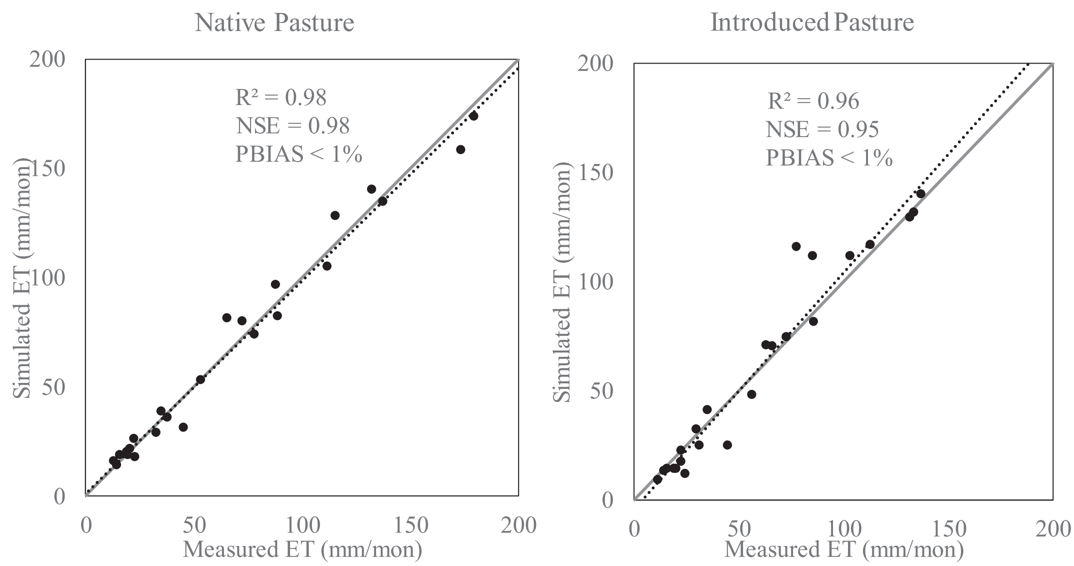

Fig. 3. Scatterplots of measured vs simulated ET at native and introduced pasture farms and model evaluation metrics.

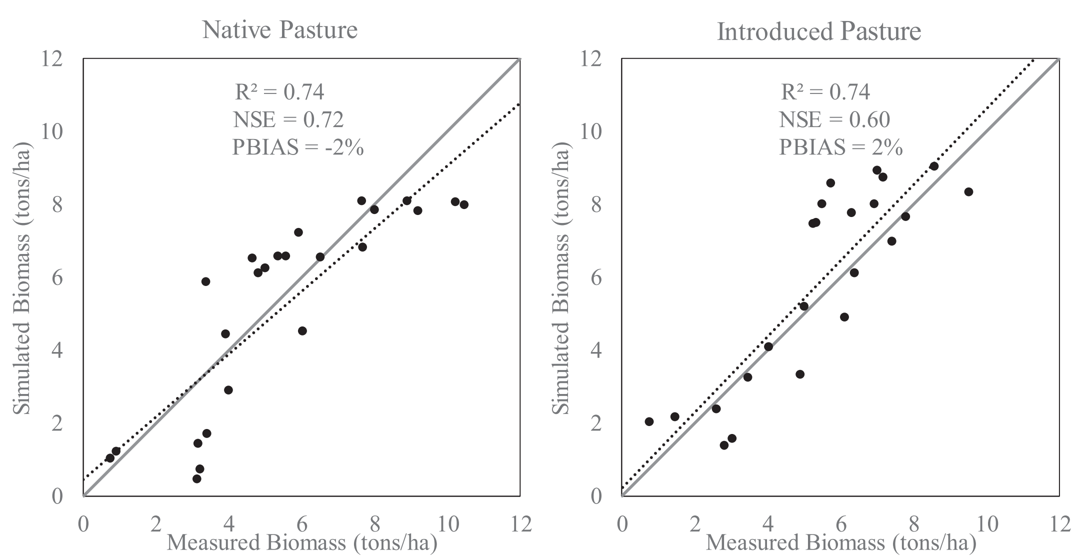

Fig. 4. Scatterplots of measured vs simulated biomass at native and introduced pasture farms and model evaluation metrics.

Table 4
Comparison of average annual ET from native and introduced pasture fields.

Pasture	Average annual (2015/2016)	
	Simulated ET	Observed ET
Native	797	802
Introduced	718	711
Percent ET difference (introduced-native)/native (%)	−10%	−11%

standard planting and harvesting conditions with no grazing, annual ET was found to be higher ($P < 0.05$) for native pasture compared to introduced pasture over the 28-year period. Lower ET from the introduced grasses (old world bluestem) could be due to the reduced transpiration, as reported by Rajan et al. (2015). In water-limited regions of the SGP, a majority of forage producers are switching to water efficient cropping systems, such as dryland agriculture or utilizing introduced pasture species (TAWC, 2011) that are capable of producing high-quality forage with limited irrigation (Philipp et al., 2005; Allen et al., 2012). Introduced species

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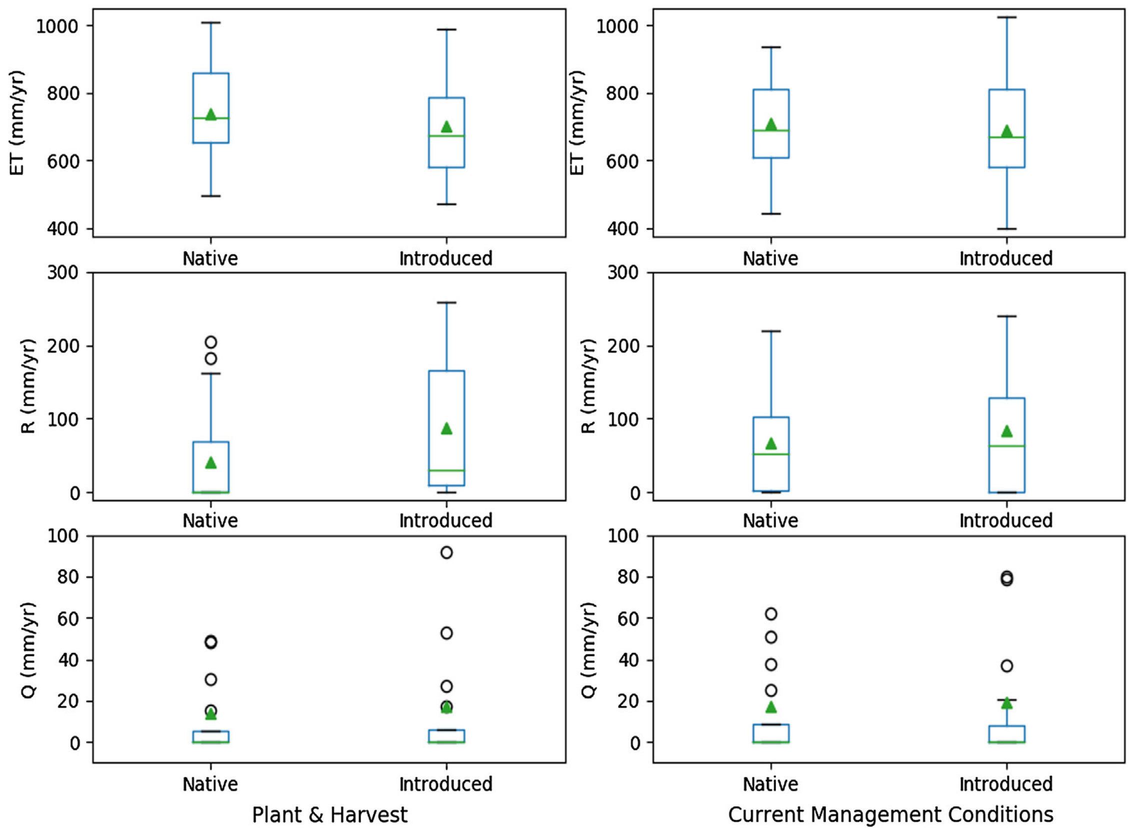

Fig. 5. Effect of grassland type on evapotranspiration (ET), groundwater recharge (R), and surface runoff (Q).

also have higher biomass production and nutritive quality compared to other naturalized grasses (Sanderson et al., 1999; Duch-Carvallo, 2005; Philipp et al., 2007).

Our results suggest that due to lower ET, introduced pasture generated more groundwater recharge (R) and surface runoff (Q), when compared to those from the native pasture (Fig. 5). The results also indicate that there was greater variability in annual hydrologic fluxes in the introduced pasture field compared to the native pasture field. This variability could have been augmented by the grazing operations in the introduced pasture and the sensitivity of introduced grass species to weather variability. Results suggest that the hydrology of native pasture is less influenced by annual weather variability (such as precipitation and temperature) and management condition (viz. grazing), while the introduced pasture is more affected by those factors (Fig. 5).

3.6. Effect of livestock stocking rate on the hydrologic fluxes

Results indicate that crop water consumption or ET from native and introduced pastures decreases with an increase in stocking rate (Fig. 6). This leads to an increase in water yield through the increase in both the surface and groundwater flows (Fig. 6). As expected, the variation in hydrological fluxes in both pasture fields increased with an increase in stocking rate. The hydrological impacts of grazing were found to be more pronounced for high stocking rate, where ET decreased significantly, leading to a significant increase in water yield. Annual ET from APEX in introduced pasture ranged from 494 ± 10 mm/yr for the high stocking rate to 700 ± 27 mm/yr for no grazing. The annual ET estimates from APEX in the native pasture ranged from 511 ± 11 mm/yr to 716 ± 24 mm/yr. The decrease in annual ET with an increase in stocking rate led to a rise in recharge, which was as high as 252 ± 25 mm/yr and 237 ± 25 mm/yr for the introduced and native pastures, respectively. Similarly, surface runoff showed a significant increasing trend ($P < 0.05$) with an increase in stocking rate. Further increasing of the stocking rate (to very high) resulted in a negligible effect on the hydrology and indicates the maximum impact was reached during the high stocking rate. This could be largely because the maximum capacity of biomass removal by grazing animals was reached when the fields were being grazed at the high stocking rate.

Overall, our results suggest that the hydrological responses of stocking rate in both pasture fields are directly linked with changes in ET, as ET decreases with an increase in stocking rate or biomass loss. Rajan et al. (2015) found similar results in the SGP, where they suggested that green biomass loss significantly alters latent heat flux (LE) or ET and sensible heat fluxes. They also reported the highest values of ET fluxes at the beginning of the grazing season, which fell gradually as the growing season progressed with increasing grazing activities and vegetation loss. Changes in ET or the water lost to the atmosphere can alter surface water availability which can further alter other hydrologic components, such as surface runoff and groundwater recharge.

4. Conclusion

Our study revealed some important factors associated with biomass and hydrology of native and introduced pasture fields in the SGP. First, the introduced pasture was found to have higher biomass, lower ET, and higher water yield (runoff and groundwater recharge) compared to the native pasture. This implies that the native pasture is less water efficient, compared to the introduced pasture; however, the trade-off is that the native pasture is more stable to weather variability (e.g., changes in precipitation patterns

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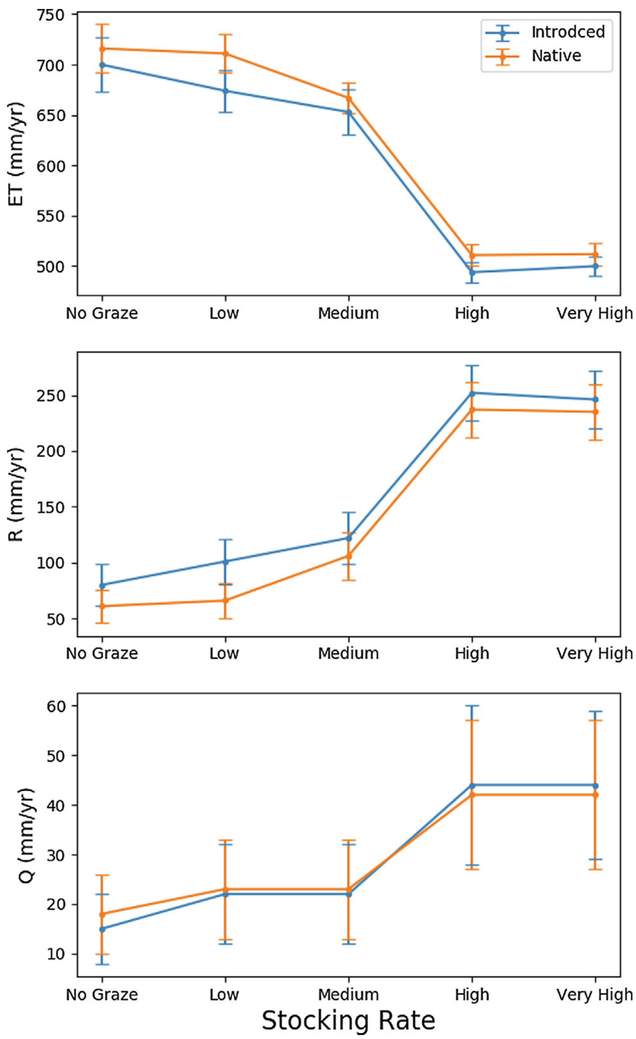

Fig. 6. Effect (Mean ± SE) of stocking rate on evapotranspiration (ET), groundwater recharge (R), and surface runoff (Q).

and increase in temperature) over a long period of time. Second, hydrologic fluxes are more sensitive to changes in stocking rate than changes in grass types/species in the SGP, suggesting the fact that grazing has a strong influence on the hydrology of SGP. Finally, the introduced pasture and higher stocking rate both contribute to an increase in water yield through increased surface runoff and groundwater recharge. However, it should be noted that even though the forage biomass potential for the introduced species is much higher, native grass is preferable to animals. These findings should provide useful guidance for future pasture management plans in the SGP.

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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