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Simulated water quality effects of alternate grazing management practices at the ranch and watershed scales

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ABSTRACT

Inappropriate grazing management with high stocking rates can result in significantly higher levels of runoff, sediment and nutrient losses to surface water resources. An assessment of water quality effects of various grazing management practices enables the selection of appropriate management practices. The overall objective of this study was to assess the impacts of alternate grazing management practices including the heavy continuous (HC), light continuous (LC) and adaptive multi-paddock (MP) grazing, and no grazing (EX; exclosure) on water quality at the ranch and watershed scales in the rangeland-dominated (71% rangeland) Clear Creek Watershed (CCW) in north central Texas using the Soil and Water Assessment Tool (SWAT). The SWAT model was calibrated and validated for water quality predictions using the measured data on county-level crop yield (1980–2013), and monthly sediment (1994–2009), total nitrogen (TN) and total phosphorus (TP) loads (1986–2009) at the watershed outlet. The ranch-scale assessment results at two study ranches indicated that when the grazing management was changed from the baseline MP grazing to HC grazing, the simulated average (1980–2013) annual surface runoff, sediment, TN and TP losses increased within the ranges of 106%–117%, 6.0–8.1 ton ha^{-1}, 8.3–11.5 kg ha^{-1}, and 1.6–2.6 kg ha^{-1}, respectively. At the watershed-scale, shifting grazing management from the baseline HC grazing to the improved MP grazing decreased surface runoff, sediment, TN and TP loads by 47.0%, 39.7%, 35.1% and 34.1%, respectively. Thus, adaptive MP grazing was found to be the best grazing management practice for the CCW in terms of water quality protection and improvement in ecosystem functions such as reduced soil erosion and increased nutrient retention at both ranch and watershed scales. However, the magnitudes of water quality benefits due to adoption of MP grazing vary according to the extent of grazing lands in a watershed.

1. Introduction

In the United States, rangelands are the predominant land cover type, accounting for about 31% of its geographical area (Havstad et al., 2007). Rangeland ecosystems are primarily grazed by livestock and wildlife, but they provide many ecosystem services essential for rural and urban populations (Wilcox, 2010), and their management has a significant influence on watershed function (Schlesinger et al., 1990; Miller et al., 2005; Wilcox, 2010; Davies et al., 2011; Al-Hamdan et al., 2015). The most common livestock grazing management practice on rangelands is continuous year-round grazing with high stocking rates (Teague et al., 2011), which often leads to overgrazing and is a major cause of unwanted changes in rangeland ecosystems. On continuously grazed commercial-scale ranches, animals continually impact preferred plants and portions of the landscape, causing localized degradation and uneven impact over the management unit. For long-term maintenance of ecosystem function, forage consumption must be moderated so that soil aggregate stability is not compromised.

Poor grazing practices lead to soil compaction and reduced infiltration capacities. This increases soil loss and facilitates nutrient movement by surface runoff, which can lead to the eutrophication and impairment of freshwater sources (Sharpley et al., 1994). Thus, grazed landscapes can be key contributors of sediment and nutrients to surface waters (James et al., 2007; Vadas et al., 2014), and they lose more nutrients than ungrazed pastures (Madramootoo et al., 1992; Gillingham and Thorrold, 2000; Sauer et al., 2000; Stout et al., 2000b; Burkart and Stoner, 2002; Babiker et al., 2004; Webber et al., 2010). It is therefore important that managers adopt grazing

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management practices that maintain or restore soil and ecosystem function and resilience (Havstad et al., 2007; Breckenridge et al., 2008; Teague et al., 2011). Soil erosion and nutrient losses from continuously grazed pastures are generally compared unfavorably to losses from pastures managed under rotational grazing (Ritter, 1988; Mathews et al., 1994; Sovell et al., 2000; Stout et al., 2000a; Webber et al., 2010; Teague et al., 2011; Weltz et al., 2011).

Adaptive multi-paddock (MP) grazing is an advanced, more effective form of rotational grazing in which cattle are stocked to match forage amounts, and management is adjusted to: (1) reduce runoff, and losses of soil, nutrients, pathogens and other biological materials from grazed lands, (2) provide more forage and greater net economic returns, (3) conserve natural resources, and (4) enhance ecosystem function and resilience by maintaining sufficient residual litter (Teague et al., 2013; Wang et al., 2016). However, simple adjustment of livestock numbers according to antecedent conditions is not the only factor that determines rangeland condition and productivity. To spread grazing pressure over the whole landscape, MP grazing divides the management unit into many smaller paddocks grazed by a single herd. Grazing each smaller paddock for a short period, that allows plants to recover quickly, provides a more effective means of reducing grazing pressure on preferred areas. As well as changing livestock numbers when growing conditions change, adaptive MP grazing also changes the length of grazing and recovery times to minimize grazing impact, keeps forage in a vegetative state for more days each year and facilitates ecosystem recovery and function (Tong et al., 2016).

The ranch managers need to be aware of ecosystem function response to different grazing management practices on soil health, hydrologic and water quality conditions in order to successfully reach their desired goals. Each ranch landscape and watershed is composed of different soils and topography with different management history. Because each area is unique, watershed models are most efficient in quantifying the impacts of conservation practices at various temporal and spatial scales (Chiang et al., 2010), provided model output is corroborated with field data (Teague et al., 2013). The major advantage of using watershed models is the rapid and cost-effective estimation of long-term soil erosion, nitrogen (N) and phosphorous (P) losses under different management practices.

The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) is widely used to simulate various hydro-ecological and environmental processes under different climatic and management conditions throughout the world (Gassman et al., 2007). It has been recently used in several grazing management impact assessment studies in Arkansas, Minnesota and Texas (Chaubey et al., 2010; Chiang et al., 2010; Wilson et al., 2014; Sheshukov et al., 2016). In these studies, the SWAT model was effectively parameterized to simulate common grazing management practices and used for evaluating the watershed-scale hydrologic and water quality impacts of different grazing management practices. As a part of our recent study (Park et al., 2015, 2017a), we have calibrated the SWAT model (version 2012 revision 629, released in June 2014) for simulating hydrology of the rangeland-dominated (71% rangeland) Clear Creek Watershed (CCW) in north central Texas using the measured standing crop biomass and soil moisture data at four study ranches within the CCW, and streamflow data at the watershed outlet over a 34-year period from 1980 to 2013. The calibrated model was then used to predict the effects of alternate grazing management practices on hydrologic processes at the ranch and watershed-scales. However, the water quality impacts of alternate grazing management practices were not studied in Park et al. (2017a). With a motivation to eventually compare the performance of SWAT model with that of another widely used model, APEX (Agricultural Policy/Environmental eXtender; Williams and Izaurralde, 2006), in a future study, we conducted a concurrent analysis using the APEX model and assessed both hydrologic and water quality impacts of traditional continuous and adaptive MP grazing practices in the CCW (Park et al., 2017b). However, Park et al. (2017b) APEX study lacked a spatial analysis to identify areas within the CCW that contribute to the greatest sediment and nutrient losses, which could be targeted for adoption of improved grazing management practices for achieving maximum sediment and nutrient reductions with minimum management costs. In addition, an assessment of the effects of precipitation amount and patterns during the growing (April to October) and non-growing seasons on herbaceous biomass production would be useful to better estimate sediment and nutrient losses during those seasons and plan implementation of grazing management practices accordingly.

The overarching goal of this study was to further calibrate the Park et al. (2017a) SWAT hydrology model for accurately simulating water quality of the CCW and assess the impacts of alternate grazing management practices on water quality at the ranch and watershed scales. The specific objectives were to: (1) calibrate the Park et al. (2017a) SWAT hydrology model for water quality predictions from the CCW using long-term measured data on sediment, nitrogen (N) and phosphorous (P) losses at the watershed outlet, (2) assess the ranch and watershed scale impacts of alternate grazing management practices on sediment and nutrient losses to surface water, and 3) map spatial distribution of sediment and nutrient losses with in the CCW resulting from alternate grazing management practices. The grazing management practices evaluated in this study include: (1) continuous grazing with high stocking rates (HC), (2) continuous grazing with light stocking rates (LC), and (3) adaptive multi-paddock (MP) grazing management, and (4) no grazing (EX; exclusion of livestock grazing).

2. Materials and method

2.1. SWAT model description

SWAT is a continuous-time, physically based, semi-distributed watershed model that predicts the effects of various land management practices on hydrologic, sediment and nutrient processes under varying climatic, soil, land use, and management conditions (Arnold et al., 1998). It delineates and divides a watershed into multiple subwatersheds, which are further subdivided into hydrologic response units (HRUs). The HRUs, which are the smallest units for computing hydrologic and water quality processes in a subwatershed, are unique combinations of soil, land use and topography characteristics (Arnold et al., 1998; Neitsch et al., 2011). The SWAT model operates on a daily time step to predict hydrology, water quality, and crop growth.

In the SWAT model, sediment yield is estimated for each subwatershed using the Modified Universal Soil Loss Equation (MUSLE), which was developed by Williams (1975). SWAT simulates N and P processes through respective complete nutrient cycles (see Supplementary Material for details). The grazing operation in the SWAT model simulates plant biomass removal and manure deposition by livestock on pasture or range HRUs over a specified period of time based on the input information on the time of initiation of grazing and the length of the grazing period, daily biomass removal by grazing (BIO_EAT), minimum plant biomass (BIO_MIN) threshold for grazing, and the daily amount of manure deposition (MANURE_KG). The amount of biomass trampled by livestock (BIO_TRMP) is an optional input. The model doesn't simulate manure application due to grazing operation on the days when plant biomass falls below the BIO_MIN, and it converts the BIO_TRMP (when specified) to residue. The model assumes that all pasture HRUs are grazed, but not overgrazed. The plant's leaf area index (LAI) is re-calculated by the model at the end of each day based on the fraction of biomass that