Journal of Hydrology: Regional Studies 15 (2018) 171–183

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Impact of grassland conversion to forest on groundwater recharge in the Nebraska Sand Hills

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ARTICLE INFO

Keywords:
Land-use change
Afforestation
High Plains Aquifer
Groundwater recharge
Numerical model

ABSTRACT

Study region: Nebraska National Forest in the High Plains Aquifer, Nebraska Sand Hills, U.S.A.
Study focus: This research aimed to investigate the effects of grassland conversions to forest on recharge rates in a century-old experimental forest. The DiffeRential Evolution Adaptive Metropolis ($DREAM_{ZS}$) global optimization algorithm was used to calibrate the effective soil hydraulic parameters from observed soil moisture contents for 220 cm deep uniform soil profiles. The historical recharge rates were then estimated by applying the numerical model HYDRUS 1-D for simulation of two plots representing grasslands and dense pine forest conditions.
New hydrological insights: The results indicate that conversion from grasslands to dense pine forests led to vegetation induced changes in soil hydraulic properties, increased rooting depth, and greater leaf area index, which together altered the water budget considerably. The impacts of land use change, expressed in percent of gross precipitation, include a 7% increase in interception associated with an increase in leaf area index, a nearly 10% increase in actual evapotranspiration, and an overall reduction of groundwater recharge by nearly 17%. Simulated average annual recharge rates decreased from 9.65 cm yr^{-1} in the grassland to 0.07 cm yr^{-1} in the pine plot. These outcomes highlight the significance of the grassland ecology for water resources, particularly groundwater recharge, in the Nebraska Sand Hills and the overall sustainability and vitality of the High Plains Aquifer.

1. Introduction

Over time, the ever-increasing alteration of landscapes and the exploitation of plants have provided various ecosystem services but also caused ill effects to the environment. For example, while the increase in agricultural lands and productivity in the last two centuries has increased the capacity to sustain unprecedented population growth, it has also caused extensive deforestation, soil erosion and degradation, desertification, loss of biodiversity, and depletion of groundwater resources.

Concerns over the magnitude of deforestation and its associated impact on global climate change has made it imperative to maintain current forest coverage and reduce net loss of forest area through reforestation and afforestation programs. Afforestation, reforestation, and natural forest expansion have reduced net loss of forest area from approximately 9 million hectares per year in the 1990s to 7.3 million hectares per year by 2005 (FAO, 2005a). Most afforestation programs, however, have not been undertaken through conversion of agricultural lands but at the expense of natural vegetation, particularly grasslands. In fact, vast areas of

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https://doi.org/10.1016/j.ejrh.2018.01.001
Received 30 June 2017; Received in revised form 7 December 2017; Accepted 4 January 2018

grasslands worldwide were found suitable for future forest restoration programs to offset anthropogenic CO_2 emissions (Bond, 2016).

In the last 100 years, natural regeneration and afforestation programs on various land uses have increased forest coverage (McCleery, 1992). Although forests provide several well documented ecosystem services (Nasi et al., 2002; Seppelt et al., 2011) a number of studies have also documented circumstances where conversions to forests have reduced streamflow (Brown et al., 2013), altered soil hydraulic properties (Kajiura et al., 2012), reduced soil moisture (James et al., 2003), and reduced recharge rates (Adane and Gates, 2015). The loss of soil moisture and groundwater recharge reductions have been attributed to the relatively higher evapotranspiration rates of the planted woody vegetation (Gates et al., 2011; Huang and Pang, 2011). Other studies have also partially associated these reductions in soil moisture and recharge rates to vegetation-induced soil water repellency (Adane et al., 2017) and greater rainfall interception of the introduced plantations (Allen and Chapman, 2001; Owens et al., 2006; Simic et al., 2014; Starks et al., 2014).

In the early-20th century, over 75% (215 million hectares) of the grassland coverage in the western United States was reported to be experiencing widespread degradation. In the Great Plains, most counties have lost at least part of their natural grassland vegetation (Klopatek et al., 1979). For instance, 85% to 95% of the native bluestem prairie vegetation in some areas had been converted to cropland (Sieg et al., 1999). The loss of grasslands has subsequently led to changes in the composition of vegetation, a loss of species diversity, and reductions in wildlife, such as the buffalo and prairie dogs in the Great Plains. While the Sand Hills grasslands are considered relatively intact at 85% of historical coverage, the region has experienced degradation related to conversion to cropland, habitat fragmentation, and overgrazing (FAO, 2005b). Changes in soils associated with grassland deterioration include a reduction in soil porosity, decrease in organic matter, and decrease in nutrient contents, as well as reductions in water-retention capacity (Burke et al., 1989). Such large-scale and rapid land use change has been known to cause significant changes to the environment including changes in hydrological regimes (Schilling et al., 2008; Spracklen and Garcia-Carreras, 2015), land degradation (Bruun et al., 2013; Ozalp et al., 2016), loss of habitat and wild life (Ochoa-Quintero et al., 2015), and contributing to climate change (Longobardi et al., 2016).

There is also a growing interest in the consequences of land use change on water resources at global, continental, and local scales (Elmhagen et al., 2015) with particular emphasis on groundwater recharge rates (recharge rates, for brevity) that feed shallow aquifers. Groundwater levels of many aquifers around the world have been decreasing over the last few decades due to excessive groundwater extraction for irrigation that surpasses groundwater recharge and replenishing rates (Scanlon et al., 2012; Terrell et al., 2002). The vulnerability of groundwater resources emphasizes the need to know reliable relationships between land use change and recharge rates, particularly in semi-arid regions where water scarcity is a critical concern. While the effect of natural vegetation conversion to agricultural land with respect to water resources has been well documented (Scanlon et al., 2007), studies on water resources impacts of other land use changes not associated with cropland are less common. In particular, the effect of grassland conversions to forests on water resources need further consideration due to the recent expansion of afforestation efforts and future forest restoration plans all over the world including in the United States (Adane and Gates, 2015; Eggemeyer et al., 2009; Huxman et al., 2005; Scanlon et al., 2009), China (Gates et al., 2011; Huang and Pang, 2011; Yang et al., 2012), and India (Calder et al., 1997).

This study evaluated the impact of land use change from grassland to forest on historical recharge rates in a century-old natural laboratory setting in the semi-arid Great Plains. HYDRUS 1-D was used to numerically simulate the plot-scale water balance at representative grassland and forest sites. The objectives of this study are: 1) to obtain effective soil hydraulic properties for the grass and dense pine profiles through inverse modeling using field observations, and 2) to evaluate the impact of grassland conversions to forests on recharge and the overall water budget.

2. Site description

The Nebraska National Forest (NNF) (Bessey Ranger District) is located in the south-central part of the Nebraska Sand Hills (NSH) and within the northern part of the High Plains Aquifer (Fig. 1; 41°51′45″N and 100°22′06″W; near Halsey, Nebraska, USA). The High Plains Aquifer covers an area of 450,000 km^2 and is ranked first in groundwater withdrawal for irrigation in the United States (Maupin and Barber, 2005; Scanlon et al., 2012). The NSH landscape is comprised mainly of eolian sand dunes that were deposited as recently as a few thousand years ago (Miao et al., 2007). The soil is approximately 92–97% sand (Wang et al., 2009) and that contributes to the greatest recharge rates in the High Plains Aquifer (Scanlon et al., 2012). The native vegetation of the NSH region consists of mixed-prairie grassland including little bluestem (*Schizachyrium scoparium*), switchgrass (*Panicum virgatum*), sand dropseed (*Sporobolus cryptandrus*), and Kentucky bluegrass (*Poa pratensis*) and is suitable to the historical land uses of ranching and cattle grazing (Eggemeyer et al., 2009). The climate is semi-arid continental with mean annual precipitation ranging between 40 and 70 cm yr^{-1} and potential evapotranspiration ranging between 30–136 cm yr^{-1} (Szilagyi et al., 2011).

The Nebraska National Forest is the largest man-made forest in the United States covering over 10,000 ha and it contains various coniferous tree species, which were planted as early as the 1930s (Hellerich, 2006). The forest is predominantly planted with ponderosa pine (*Pinus ponderosa*) and is surrounded by the native grassland ecosystem. The grass (G) plot with 10 m × 10 m dimensions is selected because the plot is the best approximation of the natural grassland conditions of the NSH within the forest (Fig. 1). The dense pine (DP) plot contains ponderosa pine trees at density rate of 700–1000 trees ha^{-1} and represents the dominant change in land use from the native grassland (Table 1). The selected dense pine plot contains the greatest pine tree plantation density of the entire forest. The forest also contains pine savannah and thinned pines plots with much less tree density that are thoroughly described in Adane and Gates (2015) and Adane et al. (2017).