Forest Ecology and Management 366 (2016) 1–10

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Severe depletion of soil moisture following land-use changes for ecological restoration: Evidence from northern China

Lei Deng[a,b], Weiming Yan[a], Yongwang Zhang[b], Zhouping Shangguan[a,b,*]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, PR China

[b] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, PR China

ARTICLE INFO

Article history:
Received 8 October 2015
Received in revised form 11 January 2016
Accepted 18 January 2016
Available online 6 February 2016

Keywords:
Arid and semi-arid
Artificial afforestation
Land use changes
Natural restoration
Precipitation
Soil water changes

ABSTRACT

Soil moisture is fundamental to ecosystem sustainability in arid and semi-arid regions, and characterizing temporal variations in soil moisture levels in response to changes in land use is important in assessing whether vegetation that has been restored as part of ecological restoration can be sustained. Such an assessment is presented here based on 78 recent publications focused on China's initiatives at ecological restoration including the 'Grain for Green' programme and the 'Three Norths Shelter Forest System' project. The study analysed 1740 observations at 83 sites in eight provinces in northern China to determine temporal and spatial variations in soil moisture and the causes of those variations. Changes in land use for restoration of ecosystems led to severe depletion in soil moisture levels – as low as 9%, determined gravimetrically – in the 0–100 cm layer of soil. The extent of depletion was influenced significantly by the choice of species for restoration (trees, shrubs, or grasses) and land use before the restoration. Deliberate restoration of vegetation may have the largest negative impact on soil moisture at sites that receive less than 600 mm of annual precipitation and may be practical only when it exceeds 600 mm. Afforestation decreased the levels of soil moisture significantly, whereas natural restoration had no significant effect on soil moisture. Therefore, natural restoration is the better option for maintaining the stability of water resources in arid and semi-arid regions. Afforestation would be a poor choice for places in which annual precipitation is close to or less than potential evapotranspiration but a better choice if annual precipitation is adequate. In planning revegetation initiatives, planners must understand that different environments support different vegetation types, and therefore require different solutions.

1. Introduction

Changes in land use and land cover and the dynamics of water use are important issues in studying global environmental change and must be clearly understood to sustain certain ecosystems (Fischer and Sun, 2001). Over the past century, afforestation and reforestation (artificial or deliberate forestation) have been implemented extensively (Del Lungo et al., 2006; IPCC, 2014), and increasing attention has been paid to their ecological benefits such as increased sequestration of soil carbon (Deng et al., 2014), reduction in water loss and control of soil erosion (Brown et al., 2007), and control of desertification and conservation of biodiversity (Porto et al., 2009). However, a major concern at present related to deliberate restoration of vegetation is its effect on water resources (Jin et al., 2011).

Soil moisture is a significant component of the overall terrestrial water resources, particularly in arid and semi-arid regions. Precipitation in these regions is unevenly distributed: most of it is received only in the rainy season that lasts for a few months, a great deal of water is therefore lost to run-off (Tsunekawa et al., 2013). Characterizing the variations in soil moisture across a range of spatial and temporal scales has important applications in both theory and practice (Ivanov et al., 2010) and provides a basis for optimal allocation of space for restoring lost vegetation (Yang et al., 2015). Spatio-temporal variations in soil moisture are affected by many factors including climate, particularly precipitation (Longobardi, 2008; Jin et al., 2011), topography (Wilson et al., 2005), soil depth (Legates et al., 2011; Venkatesh et al., 2011; Jia and Shao, 2014), vegetation type (Brown et al., 2005; Ursino and Contarini, 2006; Vivoni et al., 2008), and land use and land cover (Fu et al., 2003; Jackson et al., 2005). Vegetation and

* Corresponding author at: No. 26 Xinong Road, Yangling, Shaanxi 712100, PR China.
E-mail address: shangguan@ms.iswc.ac.cn (Z. Shangguan).

http://dx.doi.org/10.1016/j.foreco.2016.01.026
0378-1127/

land use may have a major influence on soil moisture content in arid and semi-arid regions (Chen et al., 2007; Sanchez-Mejia et al., 2014). Vegetation can mediate the effect of precipitation on soil moisture and change its *spatial* distribution (Vivoni et al., 2008) and can change the pattern of distribution of soil moisture between shallow and deep layers of soil in semi-arid regions (Yang et al., 2012). Such effects also vary depending on the plant species and lead to *temporal* variations in soil moisture (Aranda et al., 2012; Jost et al., 2012). Lastly, variations in soil moisture levels can be both temporal and spatial, changing with depth (Yang et al., 2014). Therefore, managing soil water resources efficiently both in time and in space is a major challenge in the efforts to restore vegetation in arid and semi-arid areas.

Changes in land use or land cover can strongly affect the dynamics of soil moisture in arid and semi-arid regions (Chen et al., 2007; Xiao et al., 2011). However, evaluating the effects of land use and its pattern on soil moisture is difficult because differences in land use, which change soil properties and the rate of evapotranspiration, inevitably increase soil moisture variability across the landscape (Wang et al., 2001). Xiao et al. (2011) found that shrubs (*Caragana korshinskii*) and forests (*Robinia pseudoacacia*) raised on sites that had been farmlands deplete soil moisture. Yang et al. (2014) also reported that in Gansu, China, soil moisture content decreased drastically in farmlands that were converted into perennial vegetation cover, and Du et al. (2007) found a steady decrease in soil moisture when an abandoned farmland was taken over by other forms of vegetation. Newly introduced vegetation usually consumes more soil moisture than native plants do and thus rapidly depletes local soil moisture resources (Cao et al., 2011; Yang et al., 2012). One consequence of large-scale afforestation is increasingly severe water shortages (Cao et al., 2009). It is possible that large-scale vegetation restoration projects are limited by soil moisture resources in arid and semi-arid regions (Chen et al., 2008; Cao et al., 2011). Therefore, comparing the distinctive effects of land use on soil moisture is critical to successful restoration of vegetation in the arid and semi-arid regions.

In China, widespread ecological degradation has constrained sustainable socio-economic development in recent decades, particularly before the end of the 20th century (Lü et al., 2012). Poor vegetation as a result of severe human interference is considered to be one of the major reasons (Chen et al., 2007). Since the 1950s, the Chinese government has initiated many large-scale efforts to check soil erosion and to restore damaged ecosystems (Fu et al., 2002). More than 9.27 million ha of farmlands on hill slopes, abandoned lands, and desert lands in China has been afforested or planted with grasses through such ecological restoration initiatives (Lü et al., 2012) as the 'Grain for Green' programme and the 'Three Norths Shelter Forest System' project. Although the initial goal was to control soil erosion (Cao et al., 2011; Deng et al., 2012), the interventions may indeed have strongly affected soil moisture (Cao et al., 2009, 2011). Although such programmes confirmed that poor or exploitative land-use practices dry the soil out (Cao et al., 2009), and despite many observations made at the local level, comprehensive assessments of changes in soil moisture in ecological restoration zones have been limited so far (Fu et al., 2003; Chen et al., 2007; Cao et al., 2009; Yang et al., 2014, 2015). In addition, potential land uses for ecological restoration are many and diverse, and it is necessary to study the long-term effects of previous land use on soil moisture on sites that were transformed into forests, shrub lands, or grasslands *before* restoring more farmland, grassland, abandoned land, desert land, and so on with new vegetation types.

Northern China, dominated by arid and semi-arid areas, is currently undergoing tremendous changes in land use and land cover because of the implementation of the 'Grain for Green' programme and the 'Three Norths Shelter Forest System' project. The region has a temperate, monsoonal climate with hot and dry summers and cold and dry winters. Soil moisture is lost mainly during the season of vegetation growth and cannot be completely replenished by precipitation during the rainy season because it is limited to a short period and a great deal of precipitation is lost in the form of run-off. Inadequate moisture thus inhibits sustainable growth of vegetation in such zones (Chen et al., 2007), which makes water a key factor in restoration of vegetation. It was against this background that the present study examined 78 research papers comprising 1740 observations at 83 sites in eight provinces in northern China (1) to determine temporal variations in soil moisture under seven land uses; (2) to analyse the differences in soil moisture profiles under those seven land uses; and (3) to study spatial variations in soil moisture and the causes of such temporal and spatial variations in soil moisture.

2. Materials and methods

2.1. Data compilation

All of the available peer-reviewed publications published during 2000–2015 and concerning changes in soil moisture (gravimetric water content) were collected. These publications dealt with soils from forests (trees), shrub lands, and grasslands that were once farmlands, grasslands (abandoned land), or desert lands and were converted as part of such restoration initiatives as the 'Grain for Green' programme and the 'Three Norths Shelter Forest System' project in northern China. The following criteria were used to select publications for analysis:

- inclusion of data on both the current and the past land use
- soil moisture (gravimetric) determined from various depths within the 0–100 cm layer (0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm)
- soil moisture determined during the period of maximum biomass (every year in August) and in the field (laboratory experiments excluded)
- paired-site, chronological sequence, or retrospective design
- comparable conditions (in terms of soil types and elevation)
- afforestation confined to the first rotation
- number of years since land use conversion was either clearly mentioned or directly ascertainable
- location, temperature (°C), and precipitation (mm) clearly given
- adequate replications and uniform soils (studies were excluded if the experiments were not adequately replicated or if the paired sites or sites in chronological sequence were confounded by different soil types.)

Of the 1740 observations (Appendix S1) in eight provinces in northern China (Fig. 1), 1317 showed a clear chronological sequence and 423 came from sites that had once been farmlands, grasslands, or desert lands.

The raw data were either obtained from tables or extracted by digitizing graphs using the GetData Graph Digitizer (ver. 2.24, Russian Federation). For each paper, the following information was compiled: sources of data, location (longitude and latitude), weather parameters (mean annual temperature and mean annual precipitation), current land use (grassland, restored deliberately or naturally), shrub land (conifers or broad-leaved shrubs), forest (conifers or broad-leaved trees), years since land-use conversion (afforestation, planted grass, or natural restoration), soil depth, and soil moisture in the five layers in the 0–100 cm depth. In studies with many replicates, data for the plots of the same age, edaphic conditions, and land use were pooled. Where a particular chronological sequence or retrospective study had recorded