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Research paper

The eco-hydrological threshold for evaluating the stability of sand-binding vegetation in different climatic zones

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ABSTRACT

Soil moisture dynamics are a determinant of the sustainable development of artificial sand-binding vegetation, which directly prevents and controls desertification and sand hazards, such as the sand burial of farmlands and pastures. How to maintain the stability of sand-binding vegetation is a challenge for ecologists and land managers. An eco-hydrological model coupling the dynamics of sand-binding vegetation cover and soil moisture was used to explore the effect of a stochastic daily precipitation regime on soil moisture and vegetation cover after the establishment of sand-binding vegetation. The simulation results indicate that herbaceous vegetation cover, woody vegetation cover and soil moisture increase nonlinearly with increasing annual rainfall. Specifically, herbaceous vegetation cover first increased and then decreased with increasing annual rainfall. Woody vegetation cover increased by a power-law function within the total community cover, and soil moisture increased exponentially. The eco-hydrological thresholds in different climatic zones and in typical revegetated sandy desert regions of China were determined using an eco-hydrological model. These indexes will not only help to promote dryland ecosystem management and maintain the sustainability of wind-breaks and sand-binding benefits but will also provide a quantifiable reference standard for vegetation recovery and reconstruction in sandy areas in the future.

1. Introduction

The main district requiring wind-sand hazard protection in northern China is approximately 320,000 km^2 in size. It includes sandy land or an agro-pasture ecotone east of Helan Mountain and transitional regions with sandy deserts or desert-steppe west of Helan Mountain (Li et al., 2014). The annual rainfall is more than 250 mm east of Helan Mountain and less than 250 mm west of Helan Mountain (Li et al., 2014). Introducing and establishing sand-binding vegetation is an effective method for preventing the hazard of wind-sand, controlling desertification and promoting regional ecological restoration and rehabilitation in sandy desert regions. Over the past 60 years, we have established artificial sand-binding vegetation on 6000,000 ha of wind-blown sand hazard areas of northern China, which serve as an important ecological barrier (Wang et al., 2008a; Cao et al., 2011). This barrier effectively controls wind-sand damage, promotes sandy land recovery and has achieved remarkable success (Cao, 2008; Wang et al., 2008a; Wang et al., 2008b; Cao et al., 2010; Wang et al., 2010; Cao et al., 2011; Assouline, 2013). However, many problems have arisen in practice, such as large areas of artificial sand-binding vegetation degrading over the decades (Cao et al., 2011; Li et al., 2014; Ding et al., 2015), groundwater levels beginning to decline (Li et al., 2014; Ding et al., 2015) and new desertification appearing in previously revegetated desert regions (Wang et al., 2008a; Li et al., 2014; Ding et al., 2015). Consequently, maintaining artificial sand-binding vegetation stability and the benefits of windbreaks and sand-binding sustainability has become a large challenge in ecological restoration and reconstruction in sandy areas (Cao, 2008; Wang et al., 2010; Tan and Li, 2015).

Artificial sand-binding vegetation is different from natural sand-binding vegetation (Hayse and Wissing, 1996; Li et al., 2000; Zeng et al., 2007; Dou, 2008; Li et al., 2010). Natural sand-binding vegetation is the result of adaption to long-term regional or local climatic conditions and the soil environment (Hayse and Wissing, 1996; Li et al., 2014). Natural sand-binding vegetation can maintain high stability in the context of small disturbances (Jonathan, 2003; Li et al., 2014).

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However, artificial sand-binding vegetation is established artificially with the explicit purpose of controlling wind-sand hazard and its stability often requires moderate human disturbance or ecosystem management approaches (Stampfli and Zeiter, 1999; Li et al., 2004; Assouline, 2013). A threshold is an actual requirement for managing and controlling artificial sand-binding vegetation ecosystems (Li et al., 2014). We must understand what threshold intervals will maintain artificial sand-binding vegetation in a stable state (Li et al., 2004; Briske et al., 2005; Li et al., 2014) and what threshold intervals will lead to degradation or succession. Without any significant changes in regional climate, a decrease below a lower bound of a threshold interval often produces unsustainable results for wind-breaks and sand-fixing (Li et al., 2004; Li et al., 2014). Therefore, identifying the reasonable mechanisms and establishing quantifiable threshold intervals is an essential prerequisite for managing and controlling artificial sand-binding vegetation ecosystems in dryland areas (Walker and Salt, 2008; Assouline, 2013; Li et al., 2014).

This work aimed to investigate the eco-hydrological thresholds of dryland ecosystems. The concept of a threshold has been used in the physical sciences since the late 1700 s and has been investigated extensively since the late 18th century (May 1977; May 2001; Muradian, 2001; Holling, 2003). Two main types of ecological threshold have been proposed for ecosystems, namely threshold point (May 1977; Friedel, 1991; Muradian, 2001; Walker et al., 2004; Bowker et al., 2014) and threshold zone (Bestelmeyer et al., 2004; Huggett, 2005). Many ecologists have defined an ecological threshold as a critical point at which the ecosystem moves from one steady state to another (Friedel, 1991; Muradian, 2001; Bowker et al., 2014). Critical threshold points usually indicate a discontinuous or catastrophic shift in ecosystems (Scheffer et al., 2012; Bowker et al., 2014). Other studies have shown that an ecological threshold is a transitional region or zone during the process of ecological change (Friedel, 1991; May 2001; Muradian, 2001; Wiens et al., 2002; Bestelmeyer et al., 2004; Huggett, 2005). Many studies have also integrated the two types of ecological threshold and have suggested that an ecological threshold is a point or zone where the ecosystem changes rapidly from one state to another (Radford and Bennett, 2004; Huggett, 2005). Ecological thresholds play an important role in the conservation of biological biodiversity (Huggett, 2005), succession theory in natural ecosystems (Andersen et al., 2009) and the classification of nature reserves (Briske et al., 2005; Larsen and Alp, 2015). However, current ecological threshold approaches have some disadvantages for ecosystem management (especially in arid and semiarid ecosystems); furthermore, this has not been fully validated in practice. For instance, an ecological threshold cannot reflect the distinct objective characteristics of ecological and hydrological processes in artificial sand-binding vegetation ecosystems. In particular, an ecological threshold cannot reflect the effects of hydrological processes on ecological processes or its interactive mechanisms. Therefore, it is essential to explore a new ecological threshold for managing artificial sand-binding vegetation ecosystems, not only for the theory and practice of ecosystem management but also for maintaining the effect of sand-binding and for guiding sand-binding vegetation construction in the future.

In dryland ecosystems, soil moisture is a critical variable because it integrates the effects of climate, soil, and vegetation on the water balance within ecosystems (Baird and Wilby, 1999; Rodriguez-Iturbe et al., 1999; Zalewski, 2000; Collins et al., 2014). The water balance, in turn, affects vegetation dynamics in a system (Rodriguez-Iturbe, 2000; Rodriguez-Iturbe et al., 2001; Porporato et al., 2002). In addition to being directly affected by hydrological, biological, and atmospheric processes, the soil moisture availability simultaneously controls vegetation processes such as evapotranspiration, primary production, and nutrient uptake (Rodriguez-Iturbe, 2000; Baudena et al., 2007; Collins et al., 2014). Vegetation reconstruction on arid and semiarid sandy land is at least partly dependent on the capacity of soil moisture to support it (Rodriguez-Iturbe, 2000; Li et al., 2014). Conversely, vegetation succession and rehabilitation will also change hydrological processes (Li et al., 2004; Li et al., 2007b; Assouline, 2013). Consequently, a great number of scientific questions have arisen in the process of vegetation recovery and reconstruction. For example, how much water is needed for vegetation reconstruction in different bio-climatic sandy areas? What types of sand-binding vegetation are suitable? How much sand-binding vegetation is necessary per unit area? How can sand-binding vegetation reconstruction be created in a more sustainable and reasonable way? The key to solving these problems is to determine an "ecological threshold" for maintaining the stability of sand-binding vegetation under different soil moisture conditions (Assouline, 2013). We define the concept of eco-hydrological threshold as the suitable intervals of sand-binding vegetation cover and the corresponding soil moisture in dryland ecosystems. Within suitable eco-hydrological threshold intervals, sand-binding vegetation cover and soil moisture will maintain a stable state. When the vegetation cover or soil moisture is near a lower or upper bound of an eco-hydrological threshold interval, the ecosystem state will change quickly. When both the vegetation cover and soil moisture fluctuate within eco-hydrological threshold intervals, the ecosystems will maintain a stable state. An eco-hydrological threshold is different from a conventional ecological threshold in that it is more focused on the interactive mechanisms between ecological processes and hydrological processes in dryland ecosystems.

The two primary goals of this study were as follows: (1) to investigate how vegetation cover and soil moisture vary with annual rainfall under a stochastic daily precipitation regime; and (2) to determine the eco-hydrological threshold in dryland ecosystems and in typical revegetated sandy regions of China.

2. Materials

2.1. Study site

In the Horqin sandy lands, the Onqin Daga sandy lands and the south edge of the Mu Us sandy grasslands in eastern China (see Fig. 1), the dominant sand-binding vegetation includes different types of arbours, such as *Pinus sylvestris var. mongolica* Litv and *Populus simonii Carr* (Jiao, 2012; Yang et al., 2015). In other sandy regions of China, the dominant sand-binding vegetation includes various shrubs, such as *Caragana microphylla* Lam, *Amorpha fruticosa* Linn, *Sabina vulgaris* Ant, *Hedysarum fruticosum* Pall, *Caragana korshinskii* Kom, *Atraphaxis bracteata* A. Los, *Calligonum arborescens* Litw, *Hedysarum scoparium* Fisch. Et Mey and *Haloxylon ammodendron* Bunge (Li et al., 2014; Ding et al., 2015; Yang et al., 2015). By establishing artificial sand-binding vegetation, the mobile sand dunes gradually begin to establish by reproducing a biological soil crust and herbaceous vegetation (Li et al., 2002; Li et al., 2014). Many pioneer shrubs, such as *Hedysarum fruticosum* Pall, *Artemisia wudanica* Liou et W. Wang, *Calligonum arborescens* Litw and *Atraphaxis bracteata* A. Los gradually begin to withdraw from these communities (Li et al., 2014; Ding et al., 2015). Other shrub species, such as *Caragana microphylla* Lam, *Caragana korshinskii* Kom, *Haloxylon ammodendron* Bunge and *Artemisia ordosica* Krasch can be used to form stable sand-binding vegetation communities over the long term through self-regeneration in suitable sandy areas (Li et al., 2002; Li et al., 2014). Dryland ecosystems are usually classified into four categories based on average annual precipitation: extreme arid regions with less than 100 mm; arid regions with 100–250 mm year^{-1}; semi-arid regions with 250–500 mm year^{-1}; and humid regions with 500–750 mm year^{-1} (Noy-Meir, 1973). In the eastern desert regions of China where the annual precipitation is over 300 mm year^{-1}, stable sand-binding vegetation communities form with *Caragana microphylla* Lam and other mixed shrubs (Zhang et al., 2014). In regions where annual precipitation is from 180 to 300 mm year^{-1}, stable sand-binding vegetation communities can form from the shrubs of *Artemisia ordosica* Krasch and *Caragana korshinskii* Kom (Li et al., 2007b; Li et al.,