Ecological Engineering 110 (2018) 87–98

Contents lists available at ScienceDirect

Ecological Engineering

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

Studying early stage slope protection effects of vegetation communities for Xinnan Highway in China

Wei Cao[a,b,c], Behzad Abounia Omran[b], Yakai Lei[a], Xi Zhao[e], Xiaoming Yang[a,d], Qian Chen[b,*], Guohang Tian[a,*]

[a] College of Forestry, Henan Agricultural University, 95 Wenhua Road, Zhengzhou, 450002, China
[b] Department of Food, Agricultural, and Biological Engineering, The Ohio State University, 590 Woody Hayes Dr., Columbus, OH 43210, USA
[c] College of Horticulture and Landscape Architecture, Henan Institute of Science and Technology, Eastern Hualan Avenue, Xinxiang, 453003, China
[d] Henansheng Zhumadian Agricultural School, Northern Fuqiang Road, Zhumadian, 463000, China
[e] College of Architecture, Texas A & M University, College Station, TX 77843, USA

ARTICLE INFO

Keywords:
Highway
Vegetation community
Slope protection
Soil erosion
Artificial neural network (ANN)

ABSTRACT

Highway slope landscape design in China usually specifies a single type of grass or uses randomly mixed native plants. This approach has limited slope protection effects considering plants' early growth capacity, species diversity, vegetation succession, and other factors. To address this limitation, this paper proposed a cross-disciplinary approach. First, the runoff plot method was used to study the early stage slope protection effects of seven different vegetation communities (VCs) selected for Xinnan Highway, which has steep slopes ranging from 30° to 33°. The results showed that i) the VCs that resulted in the least soil erosion contain only herbaceous plants or a mixture of herbs and shrub; and ii) the herb-vine combination had the worst performance. Hierarchical cluster analysis then classified the tested VCs into groups with similar slope protection effects and revealed that VCs with either the same or different community structures could cluster together. Further, the correlation analysis found significant relationships between soil erosion and multiple input variables, including rainfall amount and intensity, vegetation coverage, growth rates of herbs and bushes, above-ground biomass, and soil hydraulic conductivity. Lastly, based on 442 data points collected in the experiment, fine-tuned artificial neural network models were developed to predict soil erosion and achieved high accuracy with correlation coefficients ranging from 0.9713 to 0.9776. Collectively, the results of this research provide not only insights but also a practical tool for designing plant communities that can potentially achieve the best slope protection effects, especially in the early stage of slope restoration.

1. Introduction

Major highway construction projects offer significant economic and social benefits, e.g., reducing travel distance, ensuring road safety, and creating tourist attractions. Nevertheless, they may also adversely influence the surrounding environment, destroy and fragment wildlife habitats, and lead to deforestation and ecosystem degradation (Andrews, 1990; Bennett, 1991; Forman and Hersperger, 1996; Ghanbarpour and Hipel, 2009). Hence, the ecological effects of highway construction have been extensively studied to understand potential negative influences, including biodiversity loss, soil and water erosion, landscape fragmentation, blockage and barrier to organisms, etc. (Bengtsson et al., 2000; Rees, 2000; Forman et al., 2002; Chen et al., 2003; Davide, 2003; van Bohemen and Janssen van de Laak, 2003; Liu et al., 2010, 2013). These environmental impacts are not only associated with the construction process but also related to post-construction environmental recovery, in which highway slope protection faces greater challenges. As found in earlier studies, highway slopes usually have poor environmental conditions (i.e., warmer and drier) with less vegetation cover and fewer plant species than the natural environment along the highway (Pan et al., 2013). Soil erosion on slopes sweeps away fine materials and nutrients, worsening the slope environment (Thomas et al., 1999; Nevo et al., 1999; Polyakov and Lal, 2004).

It has been widely recognized that recovering and rebuilding the ecological vegetation in areas affected by highway construction is imperative to mitigate those aforementioned negative environmental impacts (Tan and Wang, 2004; Huang et al., 2010; Xia et al., 2012; Pan et al., 2013). Vegetation is an effective measure to restore the physical condition on the slopes and protect the soil against erosion by

* Corresponding authors.
E-mail addresses: chen.1399@osu.edu (Q. Chen), tgh0810@163.com (G. Tian).

http://dx.doi.org/10.1016/j.ecoleng.2017.08.033
Received 24 October 2016; Received in revised form 15 August 2017; Accepted 30 August 2017

physically binding soil and retaining surface water (Osman and Barakbah, 2011; Lin et al., 2014; Pan et al., 2015). As reported in Pan et al. (2015), the soil erosion modulus of herb vegetation community was 111.43 t/km^2·y, much lower than that of the non-vegetation area (1326.67 t/km^2 y). In China, slope bioengineering protection is one of the most important measures aiming to protect the slope, avoid water and soil loss, and improve water regime of slope soil, especially when the slope is steep (exceeding 1:1.72 or 30°). Various bioengineering protection methods used include, but are not limited to, three-dimension vegetative net, suspended net soil spray-sowing technology, hydraulic spray seeding technology, and frame method of slope protection (Tan and Wang, 2004; Lu and Yu, 2008). All of them are not only for slope greening but also for improving the road area ecological system recovery.

The recovery and stabilization of vegetation community (VC) is the first step to restoring degraded ecological systems (Wang et al., 2006; Xiao et al., 2009), for which plant selection is one of the key tasks. It is important to screen and select vegetation that could adapt to local climates as well as the poor micro-environmental conditions of highway zones. Usually, the plants should have the following characteristics: a well-developed root system, capable of covering the soil quickly, powerful budding force, good adaptation to local climate (e.g., native plants), strong drought resistance, and tolerance to barren and saline-alkali soils (Reubens et al., 2007; Dollhopf et al., 2008; Chen et al., 2009).

Mixture seeding is deemed desirable for establishing a viable plant community for highway slope protection due to the improved early growth ability (Chen et al., 2011). However, previous research (Zhou and Ma, 1990; Cleland, 2011) also showed that although diversity was positively correlated with stability, there existed a threshold value since greater diversity impairs individual species. So far, the ideal number of species in a plant community has not been identified. In practice, landscape contractors usually randomly mix local plants of different life forms (shrub, herb, etc.) or herbs with different characteristics and expect that these plants could cover the slope as quickly as possible to reduce excessive soil erosion associated with bare soil. With the increasing awareness that the poor in-slope soil conditions could influence vegetation diversity during the early restoration period (Zhang et al., 2012), researchers started assessing the short-term slope protection effects of different VCs, such as herbs, bushes, and a mixture of them (Osman and Barakbah, 2011; Kateb et al., 2013; Liu et al., 2014, 2016). So far, limited research has been conducted to screen plant species and form ideal plant communities to achieve the best slope protection effects.

Due to limited experimental conditions and data, developing accurate and reliable prediction models for soil erosion was deemed as the basis for determining effective mitigation methods (Geng et al., 2015). A number of researchers have performed regression analysis between soil erosion (e.g., runoff and sediment) and VC-related variables such as coverage, root, and above-ground biomass [AGB] (Descheemaeker et al., 2006; Liu et al., 2014; Lin et al., 2014). For example, Liu et al. (2014) revealed the logarithmic relationships between runoff coefficient or soil detachment rate and AGB, root weight density, or root length density on roadside slopes with R^2 values ranging from 0.876 to 0.950. Descheemaeker et al. (2006) presented the nonlinear relationship between runoff coefficient and the weighted average total vegetation cover with an R^2 value of 0.78. They also showed the linear relationship between soil erosion and rainfall amount. The regression analysis in these studies only captured one input variable at a time and their models were not validated for prediction.

Artificial Neural Network (ANN) had also been previously tested for soil erosion prediction and achieved acceptable performance (Harris and Boardman, 1998; Licznar and Nearing, 2003; Geng et al., 2015). As a self-adaptive machine learning method, ANN does not require any known equations and can capture both linear and nonlinear functional relationships among the studied variables (Zhang, 1998). Further exploration of ANN's application in soil erosion prediction is needed since past studies were limited to small sample sizes, e.g., nine measurements in Geng et al. (2015), and lacked fine-tuned models.

This research aims to fill these gaps by proposing a cross-disciplinary approach. The objectives are the following: 1) to pre-screen native plants and identify the best VCs for early stage highway slope protection using the runoff plot method; 2) to understand the influencing factors on slope soil erosion among variables corresponding to rainfall, soil/slope conditions, and VC characteristics; and 3) to develop and validate fine-tuned ANN models for soil erosion prediction using the data set generated in the experiment. According to the literature review, the set of input variables used in these predictive models is not only unique but also practical. The developed machine learning tool is expected to assist practitioners in identifying the best VCs for highway projects located in different geographical regions with known local rainfall data, plant characteristics and growth rates, and soil/slope conditions.

The experimental study reported in this paper is part of a multi-year research effort to investigate slope protection effects of different VCs. In this effort, Yang et al. (2009) analyzed the characteristics of different VCs in sand filled slopes based on the data of vegetation coverage, AGB, and the growth of bushes. Kang et al. (2011) studied the correlation between VC's diversity indices and soil characteristics. Zhang (2010) investigated the dynamic change of different VCs' characteristics from 2005 to 2009 and found no apparent vegetation degradation. With the confirmed stability, VCs found to have the best early stage slope protection effects in this research are likely to achieve very good, if not the best, short-term (at least 4–5 years) protection to the studied highway slopes.

2. Materials and methods

2.1. Study area

The highway development in China has made progress by leaps and bounds. At present, the total Chinese highway mileage has exceeded 100,000 km. Henan Province has about 6000 km of highway traffic mileage, ranked the first among all the Chinese provinces and autonomous regions. The Xinyang-Nanyang Highway (Xinnan Highway for short) selected for this study was located in the south of Henan, stretching over cities of Xinyang, Zhumadian, and Nanyang from east to west with a total distance of 182.80 km (as shown in Fig. 1). The route falls into a region with a tropical continental monsoon climate of northern subtropics, which has four distinctive seasons. The average temperature is 14.4 °C–15.7 °C and the average annual rainfall is 703.6–1173.4 mm. The precipitation during June to September accounts for 60–68% of the yearly rainfall (Li et al., 2016). The project area is one of the districts that have the most abundant rain resources in Henan.

The construction of this highway spanned from September 2004 to December 2006. The construction activities unavoidably caused some environmental issues including soil erosion to the surroundings. Revegetation of highway side slope became one of the means to ease these problems. The original highway landscape design used a single grass type or a random mixture of native plant species to restore the highway slopes. This approach was observed to have limited short-term and mid-term effects on highway slope protection (e.g., poor ground coverage, large soil erosion amounts after big rainfall events, and vegetation degradation after two to three years of initial establishment of the plants).

2.2. Plot installation and plant establishment

Four typical test sections along 120 km of the Xinnan Highway were selected and named as A, B, C and D (see Fig. 1), approximately 32°35′ – 32°55′6″ N, 112°32′ – 113°35′ E. Table 1 shows the slope type,