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Development of an invasive species distribution model with fine-resolution remote sensing

Chunyuan Diao, Le Wang*

Department of Geography, University at Buffalo, The State University of New York, 105 Wilkeson Quad, Buffalo, NY 14261, USA

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ABSTRACT

Saltcedar (*Tamarix* spp.) is recognized as one of the most aggressively invasive species throughout the Western United States. Mapping its suitable habitat is of paramount importance to effective management, and thus, becomes a high priority for conservation practitioners. In previous studies, species distribution models (SDMs) have been applied to predicting the suitable habitats of saltcedar at national scale, but at coarser spatial resolution (1 km). Although such studies achieved some success, they are lacking of capability to accommodate fine-scale resolution environmental variables, and therefore, fail to uncover detailed spatial pattern of habitats. The objective of this study was to develop a remote sensing driven SDM so as to characterize suitable habitats of saltcedar at very fine spatial scale (30 m). We exploited several fine-scale environmental predictors through remote sensing images, and utilized the logistic regression model to analyze the species–habitat relationship by identifying influential factors with subset selection criteria. We also incorporated the spatial autocorrelation with regression kriging method. Our results indicated that the model incorporating spatial autocorrelation achieved a higher accuracy than that of regression only model. Among 10 environmental variables, the distance to the river and the phenological attributes summarized by the harmonic analysis were regarded as the most significant in predicting the invasive potential of saltcedar. We conclude that remote sensing driven SDM has potential to identify the suitable habitat of saltcedar at a fine scale and locate appropriate areas at high risk of saltcedar infestation, which could benefit the early control and proactive management strategies to a large extent.

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1. Introduction

The invasion of exotic plants has posed significant threat to the species diversity and caused substantial economic damages at the global scale (Ficetola et al., 2007). Saltcedar (*Tamarix* spp.), an exotic woody shrub, is particularly problematic in the southwestern United States through replacing the native vegetation and depleting the river flow (Carruthers and Deloach, 2004). Along with the increasing availability of remotely sensed images, a suite of classification methods have been developed for successfully differentiating the saltcedar from native vegetation at different spatial scales (Everitt and Deloach, 1990; Groeneveld and Watson, 2008; Hamada et al., 2007; Silván-Cárdenas and Wang, 2010; Wang et al., 2013). However, these methods are mostly attempting to map the presence and abundance of established mature saltcedar with plant spectral characteristics, but are lacking capacity to predict the potential distribution of saltcedar in areas where invasion has not occurred. On the other hand, identification of potential invasive susceptible areas, particularly during the early stage of infestation, will allow resources managers to develop cost-effective control strategies. To this end, it is desired to develop appropriate methods for predicting suitable habitats of saltcedar with the integration of remote sensing and other auxiliary information.

Species distribution models (SDMs), based on the niche concept, are increasingly used to detect the spatial pattern and predict the early invasion of exotic plants by investigating the relationship between species occurrence and environmental gradients (Elith and Leathwick, 2009). By highlighting the priority susceptible locations and identifying the potential extent of infestations, SDMs can greatly assist land managers in coordinating response for effective eradication of exotic plants before they become widely established and costly to contain (Kerns et al., 2009). In recent studies, SDMs were employed for mapping the saltcedar habitat suitability at the national scale by relating the field occurrence data with land cover, topo-climatic and vegetation information (Cord et al., 2010; Jarnevich et al., 2011; Morisette et al., 2006). These studies successfully predicted the areas susceptible to saltcedar invasion and also demonstrated that the range of suitable habitat of saltcedar is much wider than that is currently invaded. However, due to the relatively coarse spatial resolution (1 km), these studies aimed at mapping the national-scale habitat of saltcedar and evaluating the relative

* Corresponding author. Tel.: +1 716 645 0474; fax: +1 716 645 2329.
E-mail addresses: chunyuan@buffalo.edu (C. Diao), lewang@buffalo.edu (L. Wang).

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ranking of habitat suitability, but not for predicting the sporadic and heterogeneous pattern of early invasion process, or assessing the absolute probability of the habitat. Accordingly, the national-scale risk mapping is still difficult for land managers to locate appropriate areas at high risk of infestation beneficial to further ground-based reconnaissance. Fine scale mapping of habitat suitability, on the other hand, can uncover the detailed spatial pattern of habitats and quantify the spatial heterogeneity of ecological structures (Borcard and Legendre, 2002; Engler et al., 2004; Gottschalk et al., 2011). As the scale becomes finer, the geographic patterns of distribution become patchier and the overall landscape fragmentation increases (Del Barrio et al., 2006). Sporadic and sparse patches undetected at the coarse scale become more distinguishing and more probable to be captured. Consequently, fine-scale mapping of suitable habitats can dramatically help local land governors investigate the invasive potential of nonnative species in the early stage and develop the corresponding control methods for saltcedar infestations in specific local areas. Despite the extensive studies on SDMs, yet fine-scale mapping is poorly explored and understood (but see Andrew and Ustin, 2009; Evangelista et al., 2008).

Compared to the coarse scale mapping, this noted dearth of research at fine scale is mostly attributable to three critical issues: the relative importance of environmental predictors, the influence of spatial autocorrelation and the accessibility of ample samples. Bioclimatic factors, such as temperature and precipitation, have proven to play a pivotal role in mapping the coarse-scale habitat suitability of saltcedar (Friedman et al., 2005; Jarnevich et al., 2011). However, variables that are previously proven effective at coarser resolution may not preserve significance at higher spatial resolution (Menke et al., 2008). Besides, spatial autocorrelation, as a measure of dependency among spatial observations, becomes more prominent at a finer scale. Hence, incorporating the spatial information becomes imperative for achieving an accurate prediction result. Finally, the number of samples required for training and validation of SDM will grow drastically at the fine scale and field campaign may not be an effective method for collecting adequate samples. Remote sensing images, with the scale flexibility, not only enhance the chance of selecting appropriate fine-scale environmental predictors, but also provide an expedient means to obtain the detailed saltcedar information, and hence more flexible and randomized occurrence records. For that reason, our study hypothesized that remote sensing images can facilitate the fine-scale habitat mapping by deriving continuous spatial measurements of both environmental variables and occurrence data.

The objective of the research is to develop a remote sensing driven SDM method at a fine scale that articulates the aforementioned three critical issues. The specific objectives are to: (1) extract appropriate fine-scale environmental predictors from remote sensing images for analyzing the species–habitat relationship, (2) assess the role of environmental predictors in determining the habitat suitability of saltcedar, (3) test whether the incorporation of spatial autocorrelation can lead to increased accuracy in estimating the saltcedar suitable habitats, and (4) evaluate the performance of fine-scale SDM by monitoring the dynamic change of saltcedar.

2. Study area and data

2.1. Study area

The study site (Fig. 1) is located along the Forgotten River reach of the Rio Grande River near the town of Candelaria, Texas, USA (104.69° W, 30.14° N). The Rio Grande River is the third longest river in the continental U.S. and the major tributary, the Rio Conchos, supplies most of the water in the Texas-Mexico border. The climate of this riparian zone is semi-arid to arid with average annual precipitation less than 30 cm and average temperature around 32 °C. The study area is about 4 km by 10 km with the topography characterized by canyons and small valleys. The elevation of this segment ranges from 700 m to 1150 m. The vegetation on both banks of the river is composed mostly of saltcedar (*Tamarix chinensis* L.) with some mixes of willow (*Salix* spp.) and mesquite (*Prosopis* spp.). The native cottonwood (*Populus* spp.), that once dominated the area, is completely absent (Silván-Cárdenas and Wang, 2010). The infestation of saltcedar varies in density and extent, partly due to differences in the local hydrologic system, ranging from individual trees to large continuous patches.

2.2. Image acquisition and pre-processing

2.2.1. Occurrence data

Due to the paucity of fine-scale samples with high locational accuracy in our study area, we attempted to acquire the occurrence data of saltcedar from high resolution Airborne Imaging Spectroradiometer for Applications (AISA) imagery. The AISA imagery had 61 bands in the spectral range 400–1000 nm and the spatial resolution was 1 m. It was acquired on December 21, 2005, which coincided with the time window when saltcedar leaves turn a yellow-orange to orange-brown color and thus can be distinguished from native willow and mesquite species more easily (Everitt and Deloach, 1990).

In order to acquire the occurrence data of saltcedar, we classified the AISA image with Spectral Angle Mapper (SAM) method (Kruse et al., 1993), which compares the image spectra to the reference spectra (endmembers) in the spectral library via the spectral angle and classifies the image spectra as the class with the smallest angle. Two field campaigns were conducted in November 2004 and December 2005 to collect sufficient ground reference samples. With a handheld GPS unit, we recorded the location of saltcedar, native woody riparian species, non-woody vegetation and other land cover types. In total there were forty-two points and thirty polygons. Point features were measured near the trunk of trees by lifting the GPS antenna up to 4 m with a telescoping pole. Additional polygons for non-vegetated land cover classes were selected directly from AISA image based on on-screen visual interpretation. A classification system encompassing the most important land cover types (twelve classes, see Fig. 2) in the study site was then designed. The sample size of these classes varied but all values fell between 90 pixels (for poverty weed) and 312 pixels (for saltcedar). For each class, 50% of samples were randomly selected for training the model and the remainder were reserved for testing. The SAM classification result was shown in Fig. 2. The overall accuracy of the classification result calculated from the testing samples was 82.5% and the kappa coefficient was 0.81. For the saltcedar class alone, the producer's accuracy was 89.3% and the user's accuracy was 94.2%. SAM classification result was resampled to 30 m resolution for maintaining the same scale with that of environmental layers, and the fraction of saltcedar was calculated. Given the classification accuracy of AISA imagery, the approximate error of the resulted saltcedar fractions was about 10%.

At the 30 m scale, the pixel with its fraction of saltcedar greater than 10% was labeled as the presence point, otherwise it was taken as the absence point. We selected 10% as the threshold in order to take into account the error of the aggregated saltcedar fractions introduced by the classification procedure. Compared to the majority rule, this partition of occurrence data is more likely to meet the pixel-based equilibrium assumption of correlative modeling of species' distributions. With the classification result of saltcedar and others, 400 presence points and 400 absence points were randomly