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Spatiotemporal heterogeneity of the potential occurrence of *Oedaleus decorus asiaticus* in Inner Mongolia steppe habitats

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A B S T R A C T

Grasshopper plagues have posed a severe threat to grasslands in Inner Mongolia, China. How to predict and control grasshopper infestations has become an urgent issue. We sampled 293 plots in Xianghuangqi County, measured the density of the most dominant grasshopper species, *Oedaleus decorus asiaticus*, and the latitude, longitude, and certain habitat factors at each plot. We estimated the grasshopper habitat suitability using a fuzzy evaluation model combined with 3S technology, and evaluated the grasshopper climatic suitability during the period 2001–2010. The integrated suitability ranks can indicate the corresponding ranks of potential occurrence of grasshoppers (POG) well. The spatial pattern of POG was closely associated with that of habitat suitability. *O. decorus asiaticus* was most likely to be found at flat sites or southern/eastern slopes with elevations of 1300–1400 m, typical chestnut soil with sand content of 60–80% in the topsoil, and medium vegetation coverage of 30–50% on temperate bunchgrass steppe. The annual variations in spatial pattern of POG were mainly due to variations in climatic suitability. Spring drought and spring high temperature might cause grasshopper plagues. This study provides an effective means for predicting the locations where grasshoppers might occur using relatively stable habitat factors and a few climatic factors.

1. Introduction

Grasshoppers are among the most devastating pests in the Inner Mongolian grasslands, which are the largest in China and represent typical Eurasian semiarid steppe ecosystems. The areas infested by grasshoppers in the Xilingol League accounted for 46.6% of all the infested area in Inner Mongolia, and the seriously infested area accounted for 44.3% in 2000–2004 (Liu and Guo, 2004). Grasshopper plagues seriously affect livestock grazing and the lives of local people. They also play essential roles in grassland desertification and degradation, and grassland ecosystem service functions. Therefore, it is necessary and important to precisely predict the spatiotemporal pattern of grasshopper occurrences and to develop effective preventive and control measures.

Weather conditions (such as rainfall, snowpack, relative moisture, lower temperature, and drought) and weather fluctuations have obvious effects on overwintering and incubation of grasshopper eggs, and on the geographical ranges and degree of hazard of grasshopper infestations (Capinera and Horton, 1989; Chen et al., 2006; Johnson and Worobec, 1988; Liu and Guo, 2004; Mattson and Haack, 1987; Mukerji and Braun, 1988; Ni et al., 2000; Schell and Lockwood, 1997; Wang and Chen, 1987). According to 32-year meteorological records (1980–2011) from a national weather station in Xilinhot (the capital of Xilingol League), this region has been experiencing a drying and warming trend during the growing season (Zhang and Liu, 2014). Given that semiarid grasslands are particularly sensitive to climate change, how the drying and warming climate has affected and will affect grasshopper infestations and grassland ecosystems needs to be understood.

Climatic processes act on relatively broad spatial scales (e.g., Xilingol League or Inner Mongolia), and thus climatic variability may be markedly exhibited over a broad area. However, it is the spatial heterogeneities of habitat elements that are important for

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grasshopper dynamics within a small area such as a county. By closely tracking habitat variations, a grasshopper population varies within its own unique suite of scales of habitat patch, possibly often occurring at some sites, while being absent at other sites. As they are herbivores, the fitness, density or abundance, and distribution of grasshoppers are closely associated with vegetation characteristics, such as plant species richness or diversity, plant community composition and structure, grass greenness, and plant nutrient content (Bazelet and Samways, 2011b; Cease et al., 2012; Ebeling et al., 2013; Kang et al., 1989; Yan, 1995; Torrusio et al., 2002; Zhang et al., 2013). Soil properties (such as soil type, texture, temperature, moisture, pH, salinity, inorganic matter content, and rockiness) affect the availability of suitable oviposition sites, incubation and mortality of eggs, hatching and development of nymphs, number and weight of oothecae, and number and reproduction of adults, as well as plant diversity, biomass, and cover (Crous et al., 2014; Liu et al., 1984; Ni et al., 2000, 2007). Furthermore, grasshoppers are closely associated with topographic elements, including landform, elevation, aspect, slope position, and cragginess (Gong et al., 1999; Sirin et al., 2010; Zhang et al., 2002). In addition, human activities such as heavy livestock grazing, afforestation, intensive reclamation, fertilization, and fire disturbance may cause grasshopper plagues by changing habitats (Cease et al., 2012; Ebeling et al., 2013; Jonas and Joern, 2007; Kang, 1997; O'Neill et al., 2003). Therefore, in order to monitor and predict grasshopper occurrences, we must explore the inherent relationships between habitat conditions and grasshopper abundance.

There have been a number of qualitative descriptions of these relationships. In quantitative analysis, biological models have often been used to forecast outbreaks of grasshoppers based on the life cycle and the process of migration, but few models consider the influence of habitats (Hernández-Zul et al., 2013). Statistical models, such as generalized linear models and multivariate binary logistic regression models, are often used to estimate grasshoppers' responses to environmental variables (Badenhausser and Cordeauc, 2012; Bazelet and Samways, 2011a; Buse and Griebeler, 2011). Ni (2002) built a fuzzy evaluation model to explore the relationships among topography, vegetation, and soil factors and grasshopper occurrence, and obtained the spatial distribution of grasshoppers in Qinghai Lake region, China, which serves as a general reference to the related studies. However, with the exception of our previous study (Zhang et al., 2012), modeling studies on how the spatial distribution of combinations of habitat factors affects grasshoppers in a large spatial range (rather than small sampled plots) have not been conducted in Inner Mongolia, although many qualitative studies have been conducted since the 1980s. In addition, we know little about how climatic and habitat factors jointly affect grasshopper abundance. The separation of habitat evaluation from climate evaluation reduces prediction accuracy.

We can interpret and retrieve some habitat variables from remote sensing images. For example, grass and non-grass species and land cover type can be interpreted. The related habitat variables that can be retrieved include vegetation coverage, greenness, leaf area index, aboveground biomass, land surface temperature, soil water content, and leaf nitrogen concentration. Up to the 2000s, some studies used remote sensing images, as well as global positioning systems (GPS) and geographical information systems (GIS), and made an effort to link a grasshopper prediction model with remote sensing, GIS, and GPS (3S) technology. Clearly, 3S technology can provide powerful tools for exploring spatiotemporal variations in grasshopper infestations and develop large-scale and real-time monitoring and prediction. However, the application of 3S technology to grasshopper infestations is just beginning in the Inner Mongolia grasslands (Duwala, 2006; Lu et al., 2009; Zhang et al., 2012).

This study was based on field data from Xianghuangqi County, southwest of Xilingol League. An evaluation system integrating climatic and habitat suitability for potential occurrence of grasshoppers (POG) was built with the aid of a fuzzy evaluation method and 3S technology to estimate hazard degree, spatial distribution, and area of grasshopper infestations. After validating the modeled results, we estimated the POG ranks from 2001 to 2010, visualized the spatiotemporal patterns of POG, and explored their relationships with climatic and habitat factors.

2. Materials and methods

2.1. Study location and organism

The study area is located in Xianghuangqi County (41°56′–42°45′N, 113°32′–114°45′E). It covers an area of 5.1×10^5 ha, of which 97.8% is occupied by steppes. The average elevation is 1300 m, the north is mostly plateau with gentle undulations, and the south is mostly hill and flatlands with large relief. The study area experiences a continental middle temperate monsoon semi-arid climate. Sandstorms or drought often occur in spring, and snowstorms in winter. The area receives annual mean sunshine of 3031.6 h. The mean annual average air temperature is 3.1 °C, and the mean monthly averages in July and January are 20.4 °C and −16.5 °C, respectively. The mean annual precipitation is 267.9 mm, 65.2% of which falls between June and August. The frost-free period is short, at approximately 120 days. The zonal native vegetation cover is temperate bunchgrass steppe, dominated by *Stipa krylovii*, *Cleistogenes squarrosa*, and *Artemisia frigida*. The other vegetation types present include temperate short bunchgrass and short semi-shrub desert steppe, and temperate grass and forb meadow steppe. The zonal soil type is chestnut soil, and the intrazonal soil types include aeolian sandy soil, saline meadow soil, saline–alkali chestnut soil, and lithosol (Yang et al., 2009).

The main grasshopper species in the study area include *Oedaleus decorus asiaticus* (Bei-Bienko 1961), *Dasyhippus barbipes*, *Bryodema luctuosum*, and *Myrmeleotettix palpalis*. Dramatic, damaging grasshopper outbreaks occurred each year from 2001 to 2010, mostly dominated by *O. decorus asiaticus*. The present study considered only *O. decorus asiaticus*, the species requiring special attention as a pest. The density peak of the adult *O. decorus asiaticus* occurs around mid-to late July, adults oviposit in the top 5 cm of the soil around late July or early August, and egg pods overwinter until nymphs hatch around early to mid-June. *O. decorus asiaticus* is an oligophagous insect, mostly favoring grass (Chen, 2007).

2.2. Evaluation of grasshopper climatic suitability

In the present study, only the main climatic factors influencing oviposition, overwintering, and incubation of *O. decorus asiaticus* were taken into account. These factors determine the abundance of successfully hatching nymphs in early summer (from mid-June to early July) under similar habitat conditions. This abundance implied the rank of potential occurrence of *O. decorus asiaticus*, which had not been influenced by other climatic factors after nymphs have hatched.

When selecting the climatic factors and evaluating the climatic suitability for POG, we used the method proposed in Guo et al. (2009a). They collected the historical records on grasshopper plagues from 1961 to 2004 in the Inner Mongolia grasslands. They also collected the historical climate data related to temperature, precipitation, and humidity. After statistically analyzing the relationships between climate data and the ranks of grasshopper density, they selected four key climatic factors: average daily air temperature in mid-to-late July of the previous year (T_1), land surface