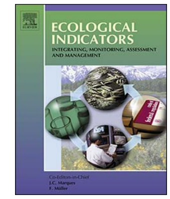
Ecological Indicators 85 (2018) 820–831

Contents lists available at ScienceDirect

Ecological Indicators

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



Predicting the effect of land use and climate change on stream macroinvertebrates based on the linkage between structural equation modeling and bayesian network

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ARTICLE INFO

Keywords:
Freshwater ecosystems
Structural equation modeling
Bayesian networks
Human disturbances
Climate change

ABSTRACT

Land use and climate change are increasingly important stressors affecting freshwater ecosystems. Although their effects on freshwater organisms have been widely studied, most studies applied traditional statistical methods, which only focus on single stressor and simple cause-effect relationships without considering the complex interactions among stressors. Therefore, we developed an integrated method by combining Structure Equation Modeling (SEM) and Bayesian Networks (BNs) to estimate the interactive effect of land use and climate change on freshwater macroinvertebrates. A field investigation was conducted in August 2009 in Taizi River Basin, Northeast China, and samples of stream macroinverterbates and water chemistry were collected from 211 sites. The SEM-BN models were developed to explore the complex relationships among land use cover (crop, forest and residential land), water quality (total phosphorus, total nitrogen and dissolved oxygen), physical factors influenced by climate change (water temperature, flow velocity), other habitat characteristics (slope and substrate composition) and macroinvertebrate EPT (Ephemeroptera, Plecoptera and Trichoptera) indices (the percentage of EPT taxa, EPT richness, EPT abundance and the Shannon-Weiner Diversity Index of EPT). Three scenarios were designed to assess the possible responses of EPT indices to land use change, climate change and their interactions. Our results showed that when the change of land use and climate were considered alone, increasing crop and urban land led to declines in EPT indices whereas moderate rise of air temperature and more rainfall had opposite effects. However, the combined effect showed that the positive effects caused by climate change could weaken some negative effects, but land use change still had stronger effect on EPT indices. Our results provided more detailed understanding on how environmental stressors affect freshwater organisms, and further catchment management should integrate the combined effect of different environmental stressors on streams.

1. Introduction

Currently anthropogenic disturbances are posing a serious threat to global rivers and streams (Tejerina-Garro et al., 2005). Through land use change, anthropogenic activities have led to significant variations in inputs of nutrients, pollutants and sediments to streams, and in-stream biological and chemical processes (Elbrecht et al., 2016; Fohrer et al., 2001; Guo et al., 2016a). Rivers and streams flowing in highly agricultural landscapes more easily import more sediments, nutrients, and pesticides, which may result in greater algal production, changes in autotroph assemblage composition and declines in bank stability (Allan, 2004; Sponseller et al., 2001). Widespread urbanization and industrialization results in significant habitat degradation and biodiversity loss in rivers and streams (Roy et al., 2003; Vörösmarty et al., 2010). The increases in impervious surface area can cause erratic hydrology and large amounts of pollutants in runoff (Paul and Meyer, 2001).

Air temperature and precipitation, which are strongly associated with climate change (Karl and Trenberth, 2003; Min et al., 2011), are important factors affecting water temperature and flow velocity. Increasing air temperature has been observed from the beginning of the 20th century (Novotny and Stefan, 2007), and due to the increase of solar radiation, surface water temperatures have also experienced some rise since the 1960s in Europe, North America and Asia (Delpla et al.,

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https://doi.org/10.1016/j.ecolind.2017.11.044
Received 22 December 2016; Received in revised form 20 November 2017; Accepted 21 November 2017
1470-160X/

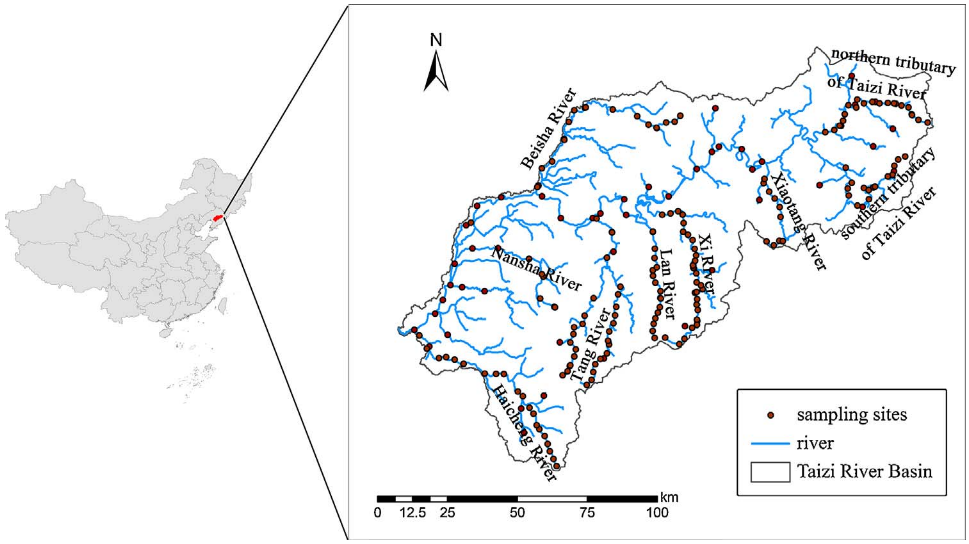

Fig. 1. Sampling sites in the Taizi River Basin, Northeastern China.

2009). Changes in precipitation are the main causes of variability in the hydrology and water balance (Novotny and Stefan, 2007). Flow velocity increases as the volume of the water in the stream increases (Ngo-Duc et al., 2007), while stream flow is generally very sensitive to precipitation with positive correlation (Groisman et al., 2001). Changes in water temperature and hydrological conditions would consequently influence water quality, habitat characteristics, and organisms living in streams (Durance and Ormerod, 2007; Guo et al., 2016b).

Stream macroinvertebrates are very sensitive to the above anthropogenic disturbances compared with other freshwater organisms, such as fish and algae (Dohet et al., 2015; Hershey and Lamberti, 1998). Their community compositions are strongly influenced by changes in stream habitats and water quality, and they have been developed as indicators to assess stream ecosystem processes and functions (Walsh, 2006). Amongst stream macroinvertebrates, Ephemeroptera, Plecoptera and Trichoptera (EPT) taxa are used for ecological studies more often compared with other taxa (Bispo et al., 2006; Peterson and Eeckhaute, 1992) because of their wide distribution, easy identification and sensitivity to disturbances. EPT taxa show lower tolerance to environmental stressors, such as land use and climate change, than other taxa. For example, EPT taxa richness is significantly lower in agricultural dominated streams than in forested streams (Lenat and Crawford, 1994). Also EPT taxa decrease as stream nutrient and contaminant levels increase in urban areas (Wilkins et al., 2015). Furthermore, macroinvertebrate abundance is predicted to reduce under warm or cool extremes (Durance and Ormerod, 2007) and the abundance and composition of EPT taxa show strong temporal variations attributed to rainfall events (Schmitt et al., 2016). Therefore, EPT taxa are often used as sensitive indicators of high-quality ecological conditions (Ferreira et al., 2014; Klemm et al., 2003).

Numerous previous studies applied traditional statistical methods, such as bivariate regression analysis (Sponseller et al., 2001) or one-way analysis of variance (Sangiorgio et al., 2014), mainly focused on the effect of a single stressor on EPT taxa without considering the complex interactions among stressors. A range of dynamic, spatially explicit and multidisciplinary models were also developed to strive for thorough quantification of ecosystem (Kragt et al., 2011), but they usually have difficulties with parameter estimation in case of limited data availability, low model transparency and excessive computation time (Landuyt et al., 2013).

Bayesian networks (BN) are increasingly used in ecological modeling and conservation in recent years (Adriaenssens et al., 2004). It is a multi-causal method with explicit constructions among diverse factors (Marcot et al., 2006), and could offer a visual framework to depict the chain of causal-effect relationships among numerous factors. BN has been used to assess the response of riparian tree species to the interactive influences of hydrological factors (Kath et al., 2016), as well as potential population response of the selected at-risk fish and wildlife species to habitat capability factors (Marcot et al., 2001). However, BN application often suffers from doubt as relies on subjective determination of structure, which is only based on expert suggestions. It would be more reliable if both expert experience and observed data could be incorporated to BNs.

Structural equation modeling (SEM) as a theoretically based method provides the assessment of relationships among multiple variables by combining causal-effect information and observed data (Grace and Pugesek, 1997; Swait, 1994). It has been used widely in social science, psychology and biology to explore the relationships among multiple variables, while the applications of SEM in ecology and environmental sciences are still limited (Grace et al., 2012; Malaeb et al., 2000). SEM is a very useful causal modeling approach, but mainly deals with linear relationships, which may result in inaccurate prediction if the relationships between independent and dependent variables are non-linear (Gupta and Kim, 2008). Bayesian networks (BNs) could overcome these limitations. Therefore, the combination of BNs and SEM could construct the relationships between environmental factors and EPT taxa, and predict future trends under combinations of different environmental stressors.

This is the first study using the combined approaches, i.e. SEM and BNs, to assess the effect of environmental stressors on benthic macroinvertebrates. The main objectives of our study were: (1) to assess robust relationships among environmental stressors and EPT taxa by SEM, and then to estimate the interaction among these multiple types of variables by BN. (2) to predict and compare the individual and combined effects of land use and climate change on EPT taxa by SEM-BN model.

2. Materials and methods

2.1. Study area and sampling sites

The Taizi River Basin is located in Liaoning Province in Northeastern China (122°25′-124°55′E, 40°28′-41°38′N) (Fig. 1), with the drainage area 13,900 km^2. It has the temperate continental monsoon climate with long cold winters, hot rainy summers, and short springs and autumns. The mean annual precipitation is about 655–954 mm, with 50% in July and August (Kong et al., 2013; Zhang et al., 2009). The elevation in the basin increases from west to east,