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Original Articles

Modeling the wetland restorability based on natural and anthropogenic impacts in Sanjiang Plain, China

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ABSTRACT

Wetlands are reducing dramatically due to rapid agricultural occupation and urbanization, resulting in severe ecosystem degradation and environmental deterioration. Comprehensive wetland restoration planning that fully considers ecosystem-level processes has the potential to improve restoration efficiency and regional sustainability. Most evaluating criteria of restorability are confined to the natural impacts on the suitability of successful wetland restoration. However, anthropogenic impacts received little attention; especially in areas where most wetlands had been encroached by intensively used farmlands. Utilization intensity is also an important factor that influences the restorability of wetlands. Here, we propose a GIS-based Restorability Index (RESI) model to evaluate the wetland restorability of the Sanjiang Plain, which is the largest marsh area of China as well as the largest grain production base. In the first step, eight criteria including natural conditions (stream order, overland flow length, saturation index, and soil characteristics) and anthropogenic impacts (land use, reclamation history, density of grain yield, and power density of agricultural machinery) were selected as influence factors of wetland restoration. For the second step, the RESI value was calculated for each grid cell via integration of spatially quantified criteria and these RESI values were classified into five levels to prioritize wetland restoration implementation. Finally, we designed a restoration plan according to the results of our restorability analysis and the requirements of regional sustainable development. This model offers a valuable tool for priority ranking of wetland restoration implementations in the agricultural landscape in a spatially explicit way.

1. Introduction

Substantial areas of wetlands have been degraded or have disappeared during the agricultural and urban expansion of recent years. Many wetland restoration scholars are increasingly focusing on efforts of planning wetland restoration at a landscape scale since a larger scale would be conducive to the integrity of wetland restoration (Moreno-Mateos and Comin, 2010; Liu et al., 2016). Many have viewed large scale wetland restoration planning as an effective way to improve water quality and regional security (Crumpton, 2001; Zedler, 2003; Verhoeven et al., 2006). In agricultural landscapes, the peak flood period could be reduced by 50% if the watershed contains 5%-10% wetlands (DeLaney, 1995). A GIS-based model is effective in producing a large-scale wetland restoration plan. Dale and Siobhan (2005) used this method to evaluate the suitability of wetland restoration for the Cuyahoga River at watershed scale, providing spatially explicit guidance for wetland restoration efforts. Francisco et al. (2014) prioritized wetland restoration and construction with the explicit purpose of water quality improvement in agricultural watersheds, utilizing a similar method. Wetland restoration planning to systematically recover wetlands at the watershed and landscape scale provides the potential for restoring ecological processes that help to maintain the stability of whole regions (Dale and Siobhan, 2005).

The likelihood of wetland restoration for sustainable long-term projects in an agricultural landscape not only involves natural factors, but also relates to factors in human disturbance. Natural factors such as hydrology, topography, soils, and geomorphology provide templates for wetland development (Bedford, 1996; Peng et al., 2010; Wang et al., 2011; Patenaude et al., 2015). These are the triggers of wetland formation and restoration, which are positively related to the likelihood of restoration success. However, anthropogenic impacts such as land use, reclamation history, power density of agricultural machinery, total fertilization amount, and farming times per year are negative impedances for the probability of successful restoration (Hatvany, 2009), since these activities affect the soil seed bank, consequentially reducing the probability of wetland restoration (Hong et al., 2012; Wang et al., 2015). All these criteria should be incorporated into the GIS model to integrate landscape variables that impact wetland biological and

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biogeochemical characteristics and sequentially prioritize implementations of wetland restoration.

Our research develops a GIS-based wetland restorability model to evaluate the probability of successful wetland restoration in the agricultural landscape of the Sanjiang Plain (China). This study assumes that anthropogenic also have impacts on the potential of wetland restoration and aims to assess the restorability from both natural and anthropogenic perspectives and then prioritize the restoration implementations and actions according to modeled restorability and requirements of regional sustainability development. Our results will guide adjustments of human activities to accelerate the restoration process. If areas with high restorability were successfully identified and restored, the efficiency for wetland restoration would increase greatly.

2. Study area

The Sanjiang plain is located in the northeast of China. It is the largest freshwater swamp alluvial plain formed by three rivers. Furthermore, it is also the most important Chinese grain production area. Agricultural and construction development resulted in drastic decreases of wetlands, overall degrading wetland function during the last four decades. Remote sensing images of the Sanjiang Plain in different periods indicate that these natural wetlands had mostly been converted into farmlands and landscape fragmentation was obviously increased (Fig. 1). The widespread loss and degradation of wetlands resulted in a series of ecological and environmental problems such as massive floods, soil pollution, and shortage of water resources. Key areas of lost and degraded wetlands need to be identified and their restoration needs to be prioritized to provide references for a regional wetland restoration plan.

3. Methods

Based on previous studies on wetland restoration (Dale and Siobhan, 2005; Ouyang et al., 2011) and the current situation of agricultural encroachment in the Sanjiang Plain, we identified eight criteria for successful wetland restoration as variables. These include: topographic saturation, soil characteristics, stream order, overland flow distance, land use, reclamation history, grain yield density, and power density of agricultural machinery. We integrated these criteria into GIS-based model to produce a restorability index (RESI) to assess the likelihood of restoration success. Then, RESI was classified to prioritize wetland restoration implementations and actions. Finally, we designed a restoration plan according to the results of our RESI analysis and the requirements of regional sustainable development (Fig. 2).

3.1. Criteria influencing restorability

Criteria related to the wetland restoration model were selected based on two aspects: natural impacts and anthropogenic impacts. All used criteria were highly related to the probability of successful wetland restoration. It should be noted that these criteria are salient for wetland restoration under an agricultural context, but they are not all inclusive.

Soil characteristics and topographic saturation are the most representative physical parameters, forming wetlands. The river order and overland flow distance are neighborhood parameters forming the landscape context for a given wetland (Dale and Siobhan, 2005). These perimeters cover most of the natural impacts relative to the wetland restoration success.

Land use/cover and land use intensity are the main impacts of human activities. They are highly related to the successful restoration of wetlands because land use types reflect the opportunity costs and land use intensity reflect the implementation costs that are affected by the probability and complexity of successful restoration (Hatvany, 2009; Wang et al., 2015; Yang et al., 2016). For example, restoration of reclaimed farmlands for many years is much more costly and complex than restoration of weeds formed by degradation of wetlands. In this study, reclamation history, grain yield density, and power density of agricultural machinery were selected as intensity criteria, affecting wetland restoration. These factors are directly related to the seed bank in the soil, which determines the degree of wetland restoration under natural conditions.

3.2. Measurement and unification of criteria

Topographic saturation, stream order, and overland flow distance were generated in ArcGIS from the digital elevation model (DEM) data which was obtained from the National Fundamental Geographic Information System (http://nfgis.nsdi.gov.cn/). The saturation index was calculated using slope and flow accumulation as follows:

$$SI = \ln(\alpha/\tan\beta) \tag{1}$$

where SI represents the saturation index without unit, α indicates the area of up-slope drainage, and β is the local slope (Beven and Kirkby, 1979).

The flow length was generated via the Flow length module of ArcGIS, which is the sum distance of each grid to the next down-stream grid. Stream orders and corresponding sub-watersheds were generated based on flow accumulation and the Strahler Stream Order. Soils were classified into three types: hydromorphic soil, high-water-content soil, and low/no-water-content soil. Each class was assigned a value representing the prospective contribution to wetland restoration.

Land use/cover was scaled from 0 to 10 according to the restoration complexity of each type. The reclamation history was generated via comparison among 1995, 2000, 2005, 2010 and 2015 land use maps that were provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC). Grain yield density and power density of agricultural machinery were queried from statistical yearbooks that were obtained from statistical department of different counties. These factors were all numerical values that could be graded.

For all factors, a unified and standardized measurement system was necessary to evaluate wetland restorability. The boundary values of each factor were determined by overall consideration of the relative importance of different factors from related publication (Dale and Siobhan, 2005; Ouyang et al., 2011) and classification methods (Natural Break Jenks). According to the effect-level of different intervals per factor, six class values were assigned to each level according to decreasing restorability (Table. 1). Level 1 indicates high restorability; level 2 indicates moderately high restorability; level 3 indicates intermediate restorability; level 4 indicates moderately low restorability; and level 5 indicates low restorability. Level 6 was excluded from the plan, as it is unsuitable for restoration. The maps were prepared in a rasterized format for subsequent analysis.

3.3. Assignment of factor weights

To build the restorability model, it is necessary to identify the relative weights of factors. Principal component analysis (PCA) is a statistical procedure to convert a set of possibly correlated variables into a set of values of linearly uncorrelated variables and it is also useful in determining relative importance of factors (Benasseni, 2010; Randjelovic et al., 2013). The quantitative process was conducted in SPSS version 15.0 (Chicago, IL, USA) as follows (Zhang and Dong, 2004).

Firstly, we extracted unified values of identified factors to randomly created 1399 points and used these values as inputs of PCA in SPSS. Six principle components (PCs) were extracted to reach the target of exceeding 80% of cumulative contributions (Joliffe and Morgan, 1992). PCs are uncorrelated variables that are obtained by multiplying the original correlated factors and by the eigenvectors (list of coefficients).