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Spatial-temporal changes of urban areas and terrestrial carbon storage in the Three Gorges Reservoir in China

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ABSTRACT

Terrestrial carbon (C) is an important element in terrestrial ecosystems. However, urban development reduces terrestrial C storage causing damage to local ecosystems. Toward this end, this research has investigated the C loss caused by urban expansion in the Three Gorges Reservoir (TGR), China. The Multi-Layer Perceptron (MLP) model was adopted to simulate a future land use map in the year 2025. The InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model was then chosen to calculate the C loss in terrestrial ecosystems (above ground carbon, below ground carbon, soil organic carbon and dead organic matter carbon) over the thirty-year period from 1995 to 2025. Results were as follows: the urban area of the TGR had increased 9788.36 km^2 from 1995 to 2015 and is predicted to increase 9834.29 km^2 from 2015 to 2025; terrestrial C lost 7.57 Tg from 1995 to 2015 and is predicted to lose another 6.04 Tg from 2015 to 2025. Terrestrial C losses are consistent with urban area expansion, showing a trend toward increase initially, followed by maintenance at a high level. Spatially, urban expansion and C loss at the TGR are predicted to begin at the Chongqing Central City then decrease outward.

1. Introduction

Terrestrial ecosystems contain carbon (C) reserves from the atmosphere, which are a vital link to carbon dioxide-driven climate change (Sharp et al., 2015). Terrestrial C serves as an indicator of ecosystem change due to the inter-relationship between the terrestrial ecosystems and climate changes (He et al., 2016). Four C pools constitute terrestrial C storage: above ground carbon (AGC), below ground carbon (BGC), soil organic carbon (SOC) and dead organic matter carbon (DOC) (Paik et al., 2009). Urban expansion alters the natural cover on land surfaces by converting natural and semi-natural land into impervious surfaces (Wenxuan et al., 2018). This conversion reduces vegetation coverage and will eventually break down the regional terrestrial C balance (Eigenbrod et al., 2011; Hutyra et al., 2011). The growing urbanization rate in China is estimated to reach 65.73% by 2030 (Zhang and Chen, 2014). As such, estimating terrestrial C loss due to urban expansion is needed in order to evaluate its long-term effects on the ecosystem.

Researchers worldwide have used the cellular automata (CA) model to simulate urban expansion at different scales. White and Engelen (1993) used a probability function to determine the probability of target cells transformed into a neighbor cell, which became the foundation of the CA model. Clarke et al. (1997) simplified the probability function and brought out the SLEUTH model. Li and Yeh (2002) introduced the ant colony algorithm, the particle swarm algorithm, the genetic algorithm and the artificial neural network algorithm into the CA model. Later studies mainly focus on algorithm improvement (Hou et al., 2004; Liu et al., 2004) and regional application (Chen et al., 2015; He et al., 2016). Although CA models have been extensively studied and developed, the weights of driven factors for urban expansion simulation were determined according to expert knowledge, which may lead to inaccurate outputs. In this study we adopted the MLP module, where the weights of input factors were determined by a machine learning process to eliminate human cognitive error, in order to produce a reliable output.

A combination of the land use change model with the C estimating model has been used frequently to assess the C loss caused by urban expansion at different scales. Nelson et al. (2010) explored the direct impact of urban expansion on biodiversity hotspots and tropical C biomass at a global scale. Lawler et al. (2014) designed a high crop demand scenario resulting in an increase of C storage in the United

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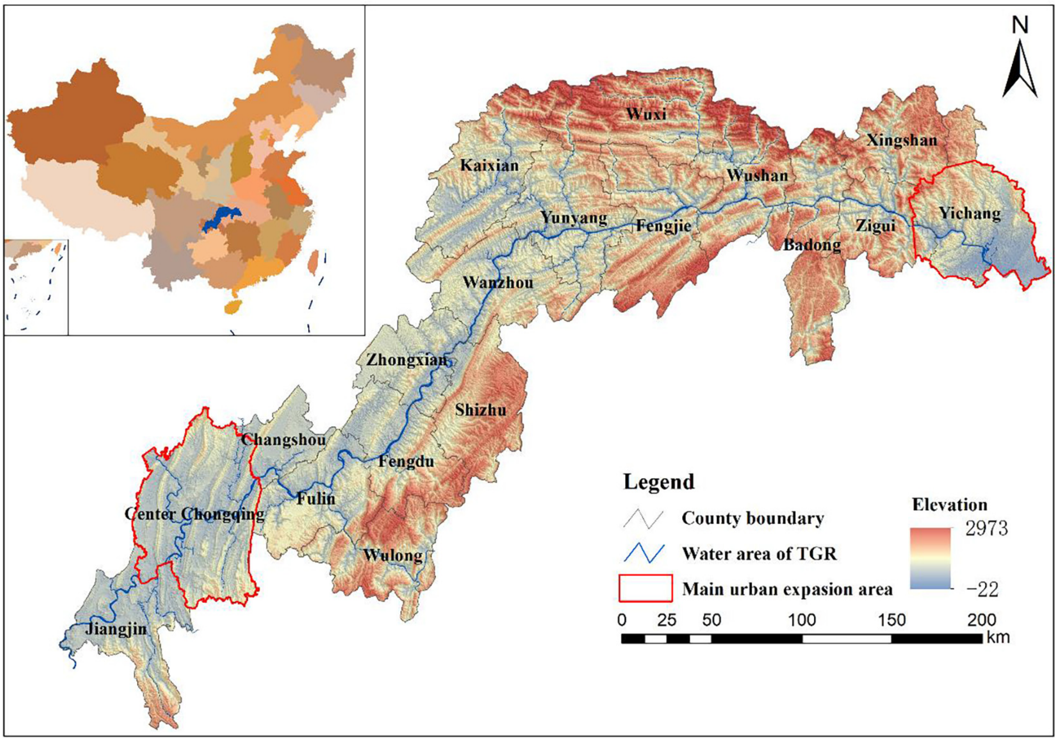

Fig. 1. Study area of the TGR.

States. He et al. (2016) assessed potential impacts of urban expansion on regional C storage in Beijing. Furthermore, different research showed that positive policy intervention can mitigate or even stop the trend of C loss while a "let it be" policy will lead to a fast C loss rate. For example, Lawler et al. (2014) adopted a strong intervention policy that leads to an increase of C storage in the United States. Jiang et al. (2017) found out that Changsha-Zhuzhou-Xiangtan agglomeration will experience the least C loss of 7.12 Tg under the Ecological Protection Scenario. Arunyawat and Shrestha (2016) reported that carbon densities in terrestrial land cover had decreased during the period of the study. Recent studies have shown that urban expansion will alter C storage; however, few studies have investigated C loss in a mountainous region.

The Three Gorges Reservoir (TGR, Fig. 1) was selected as the research area. The TGR was formed after the impoundment of the Three Gorges Dam, one of the world's largest hydropower dams operating at full capacity since 2008 (Zhao et al., 2013). Located at the transition area between eastern and western China, the per capita arable land in the TGR is small, the soil erosion is serious and the land suitable for urban construction is limited due to a vast mountainous area and hilly terraces, which also leads to a fragile ecosystem. The Three Gorges Project is regarded as one of several large-scale projects transforming China's ecology, and much attention had been given to its potential impact on the environment since the beginning of the TGR construction (Fu et al., 2010; Stone, 2008). The impoundment had submerged the villages near the Yangtze River and made the native residents seek new land for infrastructure construction and cultivated land reclamation, which significantly changed the land use and ecosystem of the TGR (Zhang et al, 2011). As such, it is necessary to explore the change of ecosystem caused by the strong human activities at the TGR.

This study estimated the C loss caused by urban expansion of the TGR with the following objectives: (1) project the land use map of the year 2025 with MLP model; (2) analyze the urban expansion pattern over the study period; (3) estimate the C loss caused by the urban expansion from 1995 to 2015 and assess the potential C loss to the year 2025. The research can provide an early warning for future C loss and promote the C reservation of the TGR. Additionally, the methodology can provide references for research of other rapidly developing regions.

2. Data and methods

2.1. Data acquisition

All land use maps were acquired through artificial visual interpretation of Landsat images (https://glovis.usgs.gov/). The land use map of 1995 was interpreted from the Landsat-TM images in the year 1995/1996, and the land use map from 2005 was obtained from the Landsat-TM images in the year 2005/2006. The land use map from 2015 was interpreted from Landsat-8 OIL images in the year 2015/2016. Given the climate of Chongqing, all remote images were collected in March or October. The land use types were farmland, forest, grassland, water areas and built-up areas. According to random sampling checks of field surveys, the accuracy of farmland and built-up areas was > 95%, while that of grassland, forest and water areas was > 90%.

The digital elevation model (DEM) was obtained from Shuttle Radar Topography Mission (https://gdex.cr.usgs.gov/gdex/), and the slope derived from the DEM. Roads and railway network data were downloaded from Open Street Map (http://www.openstreetmap.org/). All data were converted into raster images, projected into the Albers coordinate system, and resampled to a 90 × 90 m resolution.

The C density of different land use types was obtained by referring to existing studies and followed the order from the TGR to southwest China then to the whole country (Table 1).

2.2. Methods

Chongqing was under direct jurisdiction by the central government in 1997, and the Three Gorges Dam started impounding in 2003. Given these significant time nodes, we chose the land use maps from 1995, 2005 and 2015 and the simulated land use map of the year 2025 as the object land use cover images and divided them into three periods: 1995–2005 as the I period, 2005–2015 as the II period and 2015–2025