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Development of alpine wetland vegetation and its effect on carbon sequestration after dam construction: A case study of Lashihai in the northwestern Yunnan plateau in China

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ABSTRACT

The species composition and distribution, as well as the effect on carbon sequestration, was studied in newly formed alpine wetland established after dam construction in Lashihai on the northwestern Yunnan plateau in China. The plant species present, their distributions and aboveground biomass, and soil organic carbon were investigated. A submerged vegetation zone (SVZ), an emergent vegetation zone (EVZ) and a drawdown vegetation zone (DVZ) were observed along the flooding gradient from the lake towards the lakeshore five years after dam construction, on what was previously a meadow. The EVZ accounted for approximately 70% of the total zone width, and all plant species were previously recorded in Lashihai. The values of carbon storage in the vegetation were $57 \pm 10\,g\,C\,m^{-2}$, $112 \pm 4\,g\,C\,m^{-2}$, and $56 \pm 3\,g\,C\,m^{-2}$ in the SVZ, EVZ and DVZ, respectively. The values of soil carbon storage were $2234 \pm 160\,g\,C\,m^{-2}$, $2309 \pm 85\,g\,C\,m^{-2}$ and $1552 \pm 102\,g\,C\,m^{-2}$ in the SVZ, EVZ and DVZ, respectively. We concluded that the wetlands that formed following dam construction began to function as a carbon sink, and water depth was the driving force for the establishment and zonation of plant communities.

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1. Introduction

The creation of dams in wetlands and the ecological and hydrological effects are of great concern globally (Kingsford 2000; Mitsch et al., 2008; Kellogg and Zhou, 2014). More than 40,000 large dams (>15 m in height) and 800,000 small dams were built by the end of the 20th century (WCD, 2000). These dams meet over 50% of the electricity in a third of countries across the world, and some 30–40% of the 271 million hectares irrigated worldwide rely on these constructions (WCD 2000; Bezuayehu and Leo, 2007). In China, there were only 22 large dams before 1949. This number has risen to 22,000, which is the largest number of dams in the world at present (Wu et al., 2004). Damming wetlands has played a key role in social and economic development. However, the negative effect of dams on the structure and function of original wetlands has also been widely reported (Wu et al., 2003, 2004; Dai et al., 2014).

Hydrology is the primary factor determining the formation and succession of wetland vegetation (Mitsch and Gosselink, 1986); any changes in hydrological conditions will affect the structure and function of the wetland ecosystem (Gilvear and Mcinnes, 1994; Maanavilja et al., 2014). Generally, a dam is created to inundate more terrestrial land and increase the aquatic area, thereby providing conditions for succession from a terrestrial to a wetland ecosystem. Additionally, because of differences in responses to changes in hydrology, the quantitative characteristics of original communities (i.e., species composition, dominant and associated species) and their spatial distribution may be changed after dam construction (Wu et al., 2004). To date, numerous studies have been completed on original wetlands regarding their ecological functions and conservation values (Tealdi et al., 2011; Zhang et al., 2012; Hunt et al., 2013). However, little is known about the development of vegetation in newly flooded areas after dam construction.

Alpine wetlands in northwestern Yunnan Province were formed from the erosion and dissolution of limestone from ancient basins, which were isolated from other river and wetland systems. These wetlands are species-rich, act as important refugia for unique species and thus have been an important focus regarding biodiversity conservation (Yang et al., 2004; Xiao et al., 2012). Moreover, these ecosystems serve as a carbon sink in the regulation of the local carbon cycle and balance of greenhouse gases (Li et al., 2011; Guo et al., 2013). The Lashihai wetland, located in the Yunnan plateau, is of international importance under the Ramsar Wetlands Convention of 2004 because they contribute to biodiversity protection globally (Xiao et al., 2012). With rapid urbanization accompanied

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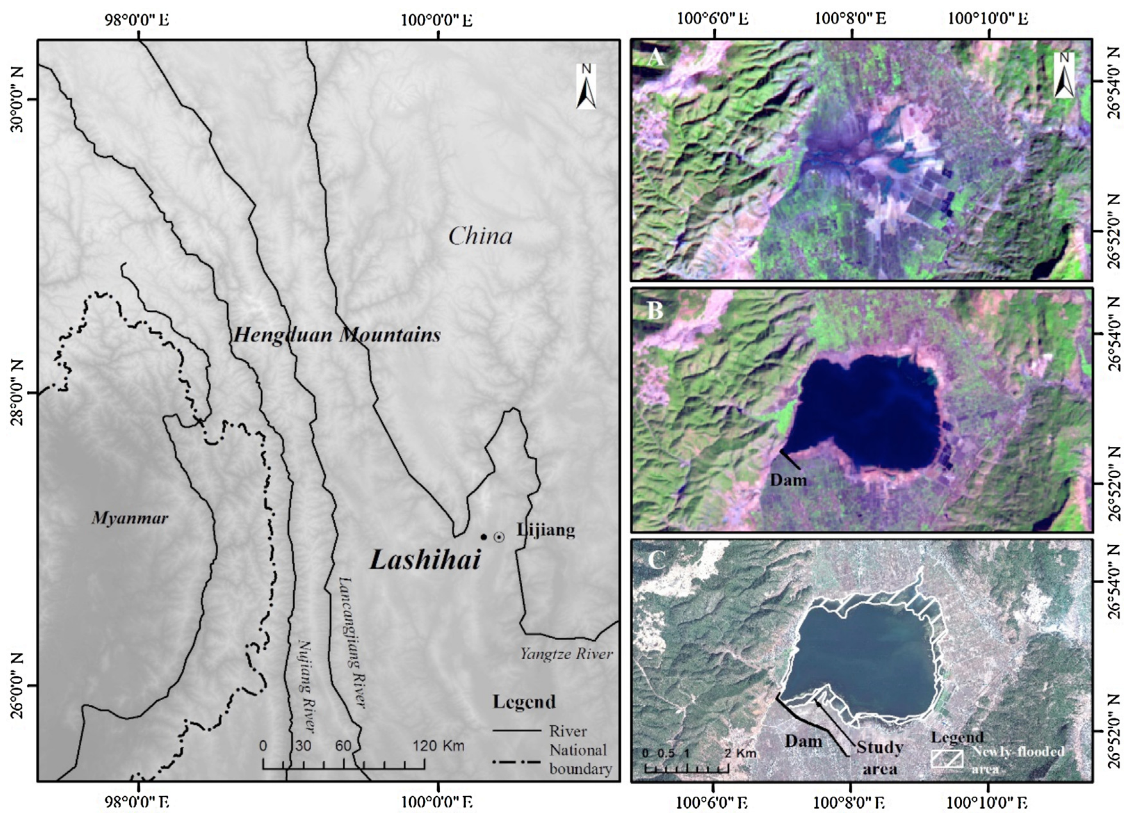

Fig. 1. The location of Lashihai and the dynamics of its wetland area. The left figure shows the position of major rivers and the Hengduan Mountains. The right figures are the Lashihai areas (a) before damming in 1986, (b) in 2008 after the first damming, and (c) in 2013 after the second damming. The white cross-hatching shows the newly flooded area. Fig. 1a shows the Landsat-TM image from January 2, 1989; Fig. 1b shows the Landsat-ETM image from February 10, 2003; Fig. 1c shows the Quickbird image from March 1, 2010.

by growth in the economy and population, the number of dams has increased rapidly (Xiao et al., 2012) and terrestrial ecosystems have been generally converted to aquatic ecosystems. Because of the considerable impact of dam construction in expanding the extent of wetlands, it is important to understand how the structure and function of these wetlands may differ from those of the original ecosystems.

The aim of this work was to understand vegetation establishment and zonation as well as the effect on carbon sequestration in this newly formed alpine wetland. More specifically, the following questions were addressed: (1) How did the vegetation adjust to the change in hydrological conditions? Did the plant species composition change? and (2) How did the carbon sequestration (i.e., plant biomass and soil organic carbon) change correspondingly?

2. Materials and methods

2.1. Study area

Lashihai is located in the southeastern Hengduan Mountains (100°06′–100°11′E, 26°51′–26°55′N, 2437 m *a.s.l.*). The area was formed from the erosion and dissolution of limestone from ancient basins. It is 10 km away from the Lijiang Ancient Town and now serves as a natural water reserve for the city (Fig. 1). The wetland has an alpine climate with a mean annual temperature of 11.8 °C. The highest average monthly temperature is 18 °C in July, and the average lowest monthly temperature is 3.9 °C in January. The annual precipitation is between 900 mm and 1200 mm, of which 80% occurs from May to October, and the average annual humidity is approximately 63%. The water level is mainly determined by precipitation and domestic consumption from Lijiang Ancient Town.

Before damming, the total flooded area of Lashihai was 0.72 km^2 (Fig. 1a), which was dominated by submerged plant species (i.e., *Butrachium bungei*, *Myriophyllum spicatum*, *Potamogeton pectinatus*, *Potamogeton malaianus*, *Potamogeton pusillus* and *Chara* spp.; Table 1). In 1994, a dam was first built in western Lashihai, and the flooded area reached 8.22 km^2 with an average water depth of 2.5–4.5 m in 2008 (Fig. 1b). Three ecological types (i.e., emergent, floating-leaved and submerged vegetation) fitting the hydrological conditions were identified; there were 21 emergent species, 15 floating-leaved species and 14 submerged species (Table 1), and the bank of the lake was mainly covered by meadow dominated by *Cynodon dactylon* (Xiao et al., 2012). This wetland can provide habitat for birds that are a national protection priority, such as *Mergus squamatus*, *Ciconia nigra* and *Grus nigricolli* (Quan et al., 2002). According to the recent surveys carried out at Lashihai, the number of winter waterfowl inhabiting the wetland is more than 100,000 annually. This wetland has been designated as an important plateau wetland that is of international importance in China, and its biodiversity protection is of global concern (Xiao et al., 2012).

In 2008, with the increased requirement of water for domestic consumption and regional economic development, the dam was reconstructed with increased height and length; the flooded area reached 10.57 km^2 (Fig. 1c), and 2.35 km^2 of the lakeshore meadow was flooded.

2.2. Field investigation and sampling

At Lashihai, the surface water is relatively stable and transparent (Li et al., 2000). Before the second dam construction in 2008, a detailed investigation of vegetation in the flooding zone was conducted in 2006 and 2007 (Xiao et al., 2012). An area approximately

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