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Spatial and temporal variation in autochthonous and allochthonous contributors to increased organic carbon and nitrogen burial in a plateau lake

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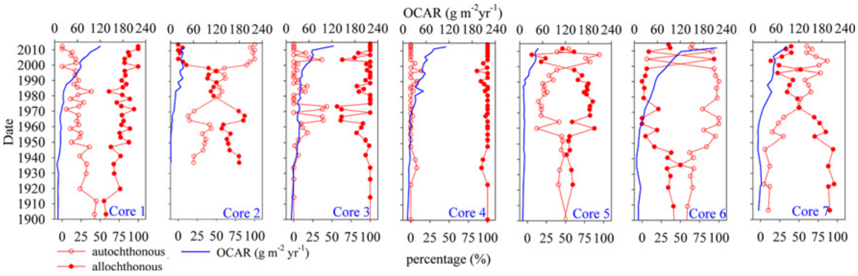
HIGHLIGHTS

- Quantitatively evaluate the contribution of autochthonous and allochthonous source to the increased OCAR and ONAR.
- Developed a multi-source mixing model based biomarkers, n-alkanes, to distinguish the autochthonous and allochthonous source.
- Fill gaps in the study of Organic-C and -N accumulation in the freshwater plateau lake.

GRAPHICAL ABSTRACT



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ABSTRACT

Increased organic carbon and nitrogen accumulation rates (OCAR and ONAR) in lake sediment significantly regulate the global carbon cycle. However, the reasons for and contributors to the increased OCAR and ONAR are unclear. Seven sediment cores, collected in July 2014 from Dianchi Lake, China, were used to evaluate the effects of autochthonous and allochthonous sources on OCAR and ONAR. The results indicate that OCAR and ONAR increased by factors of 4.33 and 7.34 over the past hundred years (1900–2000), particularly after algal blooms began to occur frequently (beginning in the 1980s). Dianchi stored 0.467 ± 0.0055 Tg (mean value ± standard deviation) organic carbon (OC) and 0.033 ± 0.0004 Tg organic nitrogen (ON) after 1986, which is almost equal to the total storage of OC and ON from 1900 to 1985 (OC, 0.468 ± 0.0022 Tg; ON, 0.032 ± 0.0002 Tg). OCAR and ONAR increases were due to increasing autochthonous production and allochthonous loading. Examination of the increased OCAR, which was estimated from a newly developed multi-source mixing model, suggests that >90% of increased OCAR was caused by allochthonous sources (such as intensified cultivation, land-use cover change, etc.) in southern and eastern Dianchi and that >70% of the increased OCAR was due to autochthonous sources in western and northern Dianchi Lake. The significant spatial and temporal variation in the contributors to increased OCAR indicates complicated migration and transformation of OC in inland lakes. Land use cover change around Dianchi and the occurrence of algal blooms regulate the contributions of allochthonous and autochthonous sources to the increased OC and ON.

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1. Introduction

Lakes are an important carbon pool. They emit greenhouse gases and store organic carbon (OC), thus playing a pivotal role in the global carbon cycle (Cole et al., 2007). Lake sediment buries large amounts of OC and thus acts as a significant carbon sink (Tranvik et al., 2009; Buffam et al., 2011). Previous studies have globally estimated that 1.88 Pg C y^{-1} of the OC that inland water receives is derived from terrestrial ecosystems. About 48% of this carbon (0.9 Pg C y^{-1}) is transported to the ocean, while the remainder reaches the lake sediment surface (0.98 Pg C y^{-1}) and 23% (0.23 Pg C y^{-1}) is eventually buried after the process of OC mineralization (Cole et al., 2007; Tranvik et al., 2009; Buffam et al., 2011). Mineralized OC is emitted as carbon dioxide (CO_2) and methane (CH_4) via microbial activity. This emission of CO_2 and CH_4 from inland waters significantly offsets the continental carbon sink and thus affects the global carbon cycle and climate change (Johnson et al., 2008; Buffam et al., 2011; Bastviken et al., 2011; Raymond et al., 2013). The mass of emitted CO_2 and CH_4 is regulated by the composition of the organic matter, temperature, oxygen exposure and the dynamic characteristics of the lake (Stief, 2007; Gälman et al., 2008; Gudasz et al., 2010; Sobek et al., 2009, 2014; Cardoso et al., 2014). Both carbon exported from land (allochthonous) and fixed by photosynthesis in aquatic ecosystems (autochthonous) contribute to the emission of CO_2 and CH_4, but with different mineralization rates (Gudasz et al., 2012). The effects of temperature and organic composition (autochthonous/allochthonous) on OC mineralization have been widely studied, and it has been proposed that OC mineralization increases with temperature, oxygen exposure and the percentage of autochthonous product (Gudasz et al., 2010, 2012; Watanabe and Kuwae, 2015; Chmiel et al., 2015). Temperature is a conventional parameter in meteorology and has been widely monitored, but the composition of organic matter has not.

Recent studies have proposed that the accumulation rate of OC has increased significantly over the last century (Kastowski et al., 2011; Larsen et al., 2011; Dong et al., 2012; Heathcote et al., 2015). The morphology, trophic state, climate and vegetation in the watershed of lakes influence OC accumulation in sediment (Alin and Johnson, 2007; Kortelainen et al., 2013; Anderson et al., 2014; Mendonça et al., 2016; Leithold et al., 2016). Global warming has also been shown to significantly increase OC burial (Heathcote et al., 2015). This finding was not confirmed by Anderson et al. (2013), who found that land-use change is more responsible than climate change for increased OC burial in Minnesotan lakes (USA). Eutrophication, caused by the enrichment of nutrients in lake water, is known to increase primary productivity and organic carbon in lakes and has been considered as another important driver of the increasing carbon burial rate (Downing et al., 2008; Heathcote and Downing, 2012; Anderson et al., 2014). In addition to representing the composition of OC in the sediment, autochthonous and allochthonous sources also determine the contribution of exotic terrestrial materials and local primary production to increased OC burial. However, the contributions of allochthonous and autochthonous sources, which regulate the composition of organic matter in the sediment, to the increased OC have not been determined. Consequently, understanding the contributions of autochthonous primary production and allochthonous terrestrial materials to increased OC burial in lake sediment is not only critical to further understand the spatial and temporal variation of greenhouse gases emitted from sedimentary OC mineralization but also to comprehend the effects of human activities and eutrophication on the global carbon cycle.

Most previous studies have focused on boreal lakes, and some have focused on temperate-zone lakes (such as in Europe, United States, etc.) to understand the process of OC burial over different time scales, the burial efficiency of OC and influencing factors to OC burial (Kastowski et al., 2011; Heathcote and Downing, 2012; Sobek et al., 2014; Ferland et al., 2014; Anderson et al., 2013, 2014; Heathcote et al., 2015; Isidorova et al., 2016). However, OC burial and its response to eutrophication and human activities in sub-tropic plateau lakes are largely unstudied. The sub-tropic plateau lakes in our study area are impacted by a variety of climatic features, such as monsoons and highland and low-latitude climates. The temperature difference between seasons is not significant; winters are relatively warm and summers are relatively cool.

n-Alkane is one of the most abundant lipid molecules, and it widely exists in plants and algae (Giger et al., 1980; Ficken et al., 2000). The carbon number distribution of *n*-alkanes in sediment can be used to trace the source of OC (Meyers, 2003; Ortiz et al., 2011; Silva et al., 2012; Fang et al., 2014). Short-chain *n*-alkanes (n-C_{14}–n-C_{20}) suggest algae, bacteria and fungi sources (Giger et al., 1980; Meyers, 2003), especially the unimodal distribution maximizing at n-C_{17}, which suggests algae and photosynthetic bacteria sources (Meyers, 2003). Mid-chain *n*-alkanes (n-C_{20}–n-C_{25}) indicate the source is submerged macrophytes (Rao et al., 2014), while long-chain *n*-alkanes (n-C_{27}–n-C_{33}) with an odd-even preference reflect a terrestrial origin (Rao et al., 2014). Study of *n*-alkanes have identified the sources of organic matter in lake sediment (Xie et al., 2003; Xiong et al., 2010; Gao et al., 2011; Fang et al., 2014; Chen et al., 2017), and a study of Dianchi Lake, the largest freshwater plateau lake in China, may fill this gap in the study of global carbon burial.

Thus, we developed a multi-source mixing model to estimate the contributions of autochthonous and allochthonous processes to OC burial and combined *n*-alkanes with OC and organic nitrogen (ON) to accomplish the objectives of this study: 1) to trace the change in OC and ON sources and burial rates over the past hundred years and 2) to distinguish the contributions of eutrophication and direct human activities on increased OC and ON burial.

2. Material and methods

2.1. Study area

Dianchi is located on the Yungui Plateau and is the largest freshwater plateau lake in China (Fig. 1). It is hypereutrophic, and algal blooms frequently occur. The concentrations of total nitrogen (TN) and phosphorus (TP) rose from 1.15 mg/L and 0.132 mg/L to 2.53 mg/L and 0.173 mg/L, respectively, from 1980 to 2010 (Zhou et al., 2016). The annual mean water temperature of Dianchi is 16 °C, and the mean depth and area are 5 m and 300 km^2, respectively. The land-use categories in the lake basin (area 2800 km^2) are mainly forest (35.71%), agriculture (22.95%) and developed land (28.55%, includes urban, residential, road and other developed land area), according to classification results from 2013 Landsat satellite imagery (Fig. 1). Dianchi is a fault depression lake. Almost all of the watershed is to the north, east and south. The Haikouzi River (blue arrow in Fig. 1) is the only outlet of Dianchi. The largest flower-producing area of Asia is located on the eastern shore of Dianchi Lake.

2.2. Methodology

2.2.1. Sampling strategy and measurement of carbon and nitrogen

Seven sediment cores were collected using a gravity-type columnar sediment sampler in July 2014. In order to reveal the spatial and temporal variation of impact factors on the increased OC and ON, these sediment cores were mainly taken from northern, eastern and southern Dianchi Lake, approximately 1 km offshore from the mouths of inflowing rivers. The sediment cores were cut into 1 cm slices and ground after being dried in a lyophilizer. Two sub-samples of 0.2 g from each ground sediment sample were used to measure the concentrations of total carbon (TC) and inorganic carbon (IC) with a TOC analyzer (Shimadzu Corp., Japan). The total organic carbon (TOC) concentration was obtained by subtracting IC from TC. Sub-samples (0.02 g) were digested by persulfate ($K_2S_2O_8 + NaOH$) at 121 °C, and total nitrogen (TN) was determined using a UV-3600