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Greenhouse gas emissions from different land-use areas in the Littoral Zone of the Three Gorges Reservoir, China

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ABSTRACT

A series of ecological projects, including forest and dike-pond projects, were constructed in the littoral zone of the Three Gorges Reservoir (TGR) to maintain the ecological safety of this area. Previous ecological designs mainly focused on the functions of ecological engineering for environmental purification, economic value and increased biodiversity. However, the variations in land-use may alter the emissions of greenhouse gases (GHGs), which were ignored in our previous design. In this paper, the carbon sequestration benefits of ecological engineering were evaluated after dynamically monitoring the GHG emissions from different land-use sites during the growing (April-September) and submerged (October-March) seasons. The results showed that CH_4 fluxes in the dike-ponds (3.76 CH_4-mg m^{-2} h^{-1}) and rice paddies (6.09 ± 1.60 mg-CH_4 m^{-2} h^{-1}) were significantly higher than those in the natural littoral zone (0.77 ± 0.27 mg-CH_4 m^{-2} mg-CH_4·m^{-2} h^{-1}) and forest project (0.57 ± 0.31 mg-CH_4 m^{-2} h^{-1}) during the growing season. There were no significant differences in the CO_2 fluxes from different land-use sites. The emission of N_2O from different land-use sites was low and ranged from −0.02 to 0.07 mg-N_2O m^{-2} h^{-1}. The growing season contributed to more than 76% of the cumulative annual GHG emissions. Direct GHG emissions and the carbon sequestration ability of species determined the net carbon sinks in the littoral zone. Net carbon sinks in the forest projects with different understory plant communities showed a small variation, with a range of −2.58 to 3.40 t-CO_2 ha^{-1} $year^{-1}$, but the design of the dike-pond projects should favor species that are positive net carbon sinks, e.g., *Sagittaria* (19.76 t-CO_2 ha^{-1} y^{-1}) and *Canna generalis* (16.79 t-CO_2 ha^{-1} y^{-1}), rather than those that are negative net carbon sinks, e.g., *Trapa natans* (−11.79 t-CO_2 ha^{-1} y^{-1}).

1. Introduction

The littoral zone, caused by water level variations in the rivers, lakes and reservoirs, is the eco-tone of terrestrial and aquatic ecosystems. The annual water level of the Three Gorges Reservoir (TGR) varies from 145 m during the summer to 175 m during the winter, which creates a very large 348.9 km^2 littoral zone (Zhang, 2008). The littoral zone absorbs nitrogen and phosphorus and acts as a buffer zone (Yuan et al., 2013) between the upland, in which the dominant land-use type is agriculture, and TGR. Thus, ecological safety in the littoral zone is directly related to the security of the TGR and the middle and lower reaches of the Yangtze River. However, the littoral zone faces many challenges and threats such as water pollution, soil erosion and biodiversity losses. Before the construction of the dam, 53.68% of the littoral zone with a slope of less than 15° (approximately 187.3 km^2) was mostly farmland (Yuan et al., 2013). Farmers often plant crops (mainly rice) in the littoral zone when the water level of the TGR declines during the spring, but these traditional farming activities use a substantial amount of fertilizer and pesticides, which threaten the water quality and ecological safety of the TGR.

The construction of ecological engineering in the littoral zone has been regarded as the most effective way to obstruct and eliminate organic pollutants from the upland (Mitsch and Jørgensen, 2004; Hoffmann and Baattrup-Pedersen, 2007; Mitsch et al., 2008).

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Research has proven that ecological engineering designed for wetland restoration plays an important role in reducing the nutrient load (Mitsch and Jørgensen, 2004) and reconstructing the hydrological connectivity of the wetland system (Hoffmann et al., 2011; Audet et al., 2013).

Recently, the emission of greenhouse gases (GHGs) from natural water bodies and wetlands (e.g., Olson et al., 2013; Xu et al., 2014) and even from wetland restoration engineering, caused the concern of environmentalists (Mitsch and Jørgensen, 2004; Audet et al., 2013). Studies show that the construction of ecological engineering likely increases the emission of N_2O and CH_4 (Freeman et al., 1997; Whiting and Chanton, 2001; Verhoeven et al., 2006), which likely offsets the potential wetland carbon sinks produced by plant photosynthesis.

The construction of ecological engineering should be based on ecological engineering principles (Odum and Odum, 2003) and minimize any potential negative effects. Our previous study certified the ecological and economic values of ecological engineering (Li et al., 2013) but ignored the potential variations in GHG emissions and carbon sequestration, which is unsuitable to optimize the ecological design in the littoral zone. The goals of this paper were as follows: 1) to determine whether the implementation of ecological projects in the littoral zone have a negative impact on GHG emissions, 2) to evaluate the net carbon sink of ecological engineering, and 3) to provide suggestions to optimize the design of ecological engineering to reduce the emission of GHGs from the TGR.

2. Materials and methods

2.1. Study sites

The ecological projects were located at the Beijia Creek (108°34′E, 31°9′N) near the Pengxi River, which is a secondary branch of the Yangtze River in Kaixian, Chongqing (Fig. 1). To ensure the ecological safety of the reservoir and eco-friendly utilization of the land resource, the dike-pond and forest projects were constructed to be 4.26 and 2.55 hm^2 in April, 2009 (Fig. 2). The littoral zone between 160 and 175 m is usually not submerged during the April-September period and does not experience frequent flood disturbances during the summer (Fig. 3), which is suitable for growing plants. The construction of ecological engineering was mainly carried out in this area. The dike-pond project is an important part of the traditional Chinese agricultural heritage (Li et al., 2011), which dates back to the invention of mulberry fish pond systems in the Pearl River Delta in China (Weng, 2007). Dike-ponds with different sizes and shapes were designed, and more than ten species that successfully endured the seasonal variations in the water level were planted. Similarly, trees and shrubs with a strong tolerance to water variations, including *Taxodium distichum*, *Taxodium ascendens* and *Glyptostrobus pensilis,* were selected to construct the forest projects between 160 and 175 m in the littoral zone, which has the ability to purify upland run-off and stabilize the bank. When the water level declines annually in April, crops are usually planted in the littoral zone above 160 m. Based on the different land-use characteristics of the littoral zone, the experimental sites were divided into five types: the littoral zone (LZ) without any human disturbance, natural pond (NP) in the littoral zone, traditional agriculture (TA) managed by local farmers, dike-pond projects (DP) and forest projects (FP) with close-to-nature management (Fig. 2).

2.2. Data collection

Static and floating closed chambers were used to measure the GHG emissions in unsubmerged and submerged environments, respectively. The chambers (30 cm wide, 30 cm long, and 40 cm high) were made of PVC. On the top surface of the chambers, there was a pipe (0.20 mm in diameter) connected to the ambient atmosphere to collect gas samples. Details about the chambers were described by Chen et al. (2008). Gas sampling was conducted between 9:00 and 11:00 am in June, 2014 (GS) and in January, 2015 (SS). Seven air samples from each chamber were taken at 5 min intervals (0, 5, 10, 15, 20, 25, and 30 min) after closing the enclosure. When sampling began, a 5 ml airtight vacuum vial was connected to a pipe for 30 s. Samples were taken back to the lab and stored in a 4 °C fridge until analysis. For the submerged environment, floating closed-chambers were fixed with anchors to avoid drifting. The CH_4, CO_2 and N_2O concentrations were monitored by gas chromatography (PE Clarus 500, PerkinElmer, Inc., USA). A FID (flame ionization detector) operating at 250 °C was used for CH_4 and CO_2 detection, and an ECD (electron capture detector) at 350 °C was used for N_2O detection. The packed column was a 2 m Porapak 80/100 Q operating at 60 °C with N_2 acting as a carrier gas flowing at 20 ml min^{-1}.

The CH_4, CO_2 and N_2O fluxes (Chen et al., 2009) were calculated as follows:

$$J = \frac{dc}{dt} \cdot \frac{M}{V_0} \cdot \frac{P}{P_0} \cdot \frac{T_0}{T} . H$$

where dc/dt is the rate of concentration change; M is the molar mass of the analyzed gases; P is the atmosphere pressure at the sampling site; T is the absolute temperature at the sampling time; V_0, P_0 and T_0 are the molar volume, atmosphere pressure, and absolute temperature at standard conditions, respectively; and H is the chamber height over the surface.

Environmental factors, including ambient temperature, community type, community height and biomass, were measured from each 1 × 1 m sample area during the growing season. The sediment thickness and water depth of the natural ponds and dike-ponds were also recorded with a ruler. Both the aboveground and underground biomasses were harvested from sample areas. The operating procedures were as follows: sampling, washing the roots, classification, sample drying for 48 h at 60 °C and calculating the biomass.

2.3. Vegetation characteristics and sampling

According to variations in the water level and plant growth characteristics, the annual feature of the littoral zone was divided into two main periods: the growing season from April to September, with a water level below 160 m, and the submerged season from October to March, with a water level above 160 m (Fig. 3). During the growing season, the characteristics of the plant communities in the littoral zone were apparent. The sampling sites were set up according to the plant community characteristics (Table 1). Four dominant communities were selected to monitor the GHG emissions from the LZ, DP and FP. Only one dominant community was selected for the TA, there were no plants for the NP. Paddy fields (*Oryza sativa*) in the littoral zone were selected to represent the TA. Four dominant species, namely *Cynodon dactylon*, *Setaria viridis, Polygonum hydropiper* and *Echinochloa crus-galli var. mitis*, were chosen for GHG emissions testing in the LZ. In the DP, four economically important plants, *Sagittaria trifolia*, *Canna generalis*, *Nelumbo nucifera* and *Trapa natans,* were selected. Four dominant understory plant communities, namely *Aeschynomene indica*, *Conyza japonica*, *Cyperus rotundus* and *Cyperus michelianus*, were chosen to test the GHG emissions in the FP. Three replicates were established for each of the dominant communities in the LZ, DP and FP. In total, twelve replicates were set up for the LZ, DP and FP. Similarly, twelve replicates were established for the TA and NP along the elevation gradient from 160 m to 175 m. During the submerged season, the littoral zone was submerged in deep water, so a separate collection