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Responses of soil nutrient concentrations and stoichiometry to different human land uses in a subtropical tidal wetland

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ABSTRACT

We studied the impacts of anthropogenic changes in land use on the stoichiometric imbalance of soil carbon (C), nitrogen (N), phosphorus (P) and potassium (K) in *Phragmites australis* wetlands in the Minjiang River estuary. We compared five areas with different land uses: *P. australis* wetland (control), grassland, a mudskipper breeding flat, pond aquaculture and rice cropland. Human activity has affected the elemental and stoichiometric compositions of soils through changes in land use. In general, soil C and N concentrations were lower and total soil K concentrations were higher at the sites under human land uses relative to the control site, and total soil P concentrations were generally not significantly different. The close relationship between total soil C and N concentrations in all cases, including fertilization with N, suggested that N was the most limiting nutrient in these wetlands. Lower soil N concentrations and similar soil P concentrations and higher soil K concentrations under human land-use activities suggest that human activity has increased the role of N limitation in these wetlands. Only grassland use increases soil N contents (only in the 0–10 cm of soil). Despite N fertilization, lower soil N concentrations were also observed in the rice cropland, indicating the difficulty of avoiding N limitation in these wetlands. The observed lower soil N:P ratio, together with higher soil P and K availabilities in rice croplands, is consistent with the tendency of human activity to change the competitive relationships of plants, in this case favoring species adapted to high rates of growth (low N:P ratio) and/or favoring plants with high demands for P and K. Both, soil C storage and respiration were higher in grasslands, likely due to the introduction of grasses, which led to a high density of plants, increased grazing activity and soil compaction. Soil C storage and respiration were lower under human land uses, except in the rice cropland, with respect to natural wetland. Using overall data, soil C storage and respiration were correlated, indicating that soil respiration was correlated with plant productivity. In this wetland area the impacts of different human land-uses on soil stoichiometry and C-cycle can be very different depending on the activity. Further regeneration of natural communities can be determined by the previous type of land-use.

1. Introduction

The quantity and relative supply of nutrients in agricultural soils have important implications for human nutrition and global biogeochemical cycles. Human interventions can strongly alter soils and the nutrient pools of carbon (C), nitrogen (N) and phosphorus (P) by increasing nutrient inputs (e.g. fertilization and increased weathering), by changing the structure of plant communities and by changing nutrient export (e.g. crop harvesting and increased erosion). Whether and how humans affect the relative balance of soil nutrients (C, N and P) through induced changes in land use remain unclear, especially in terrestrial ecosystems. Previous studies have shown a close relationship between human disturbances, such as N deposition, climate change, species invasion or increases in atmospheric CO_2, and elemental and stoichiometric shifts in plants and soils (Melillo and Field, 2003; Sardans and Peñuelas, 2012; Sardans et al., 2012a,b; Tian et al., 2010; Vitousek, 2004). Much less information, in contrast, is available on the impact of land-use changes on soil stoichiometry (Sardans et al., 2012b).

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C, N and P are strongly intertwined biochemically. The relative dynamics of these elements, however, are poorly quantified, and dependencies between elements have not been well investigated (Ågren, 2008). Well-balanced C:N:P ratios of 186:13:1 and 60:7:1 for soil and soil organisms, respectively, have been determined on a global scale (Cleveland and Liptzin, 2007), or recently for wetland soils 539:28:1 (Xu et al., 2013). Whether wetland soil also has a balanced C:N:P ratio under different intensities of human disturbance or not, however, remains unknown.

Estuarine wetland is influenced by rivers and tides, so the elemental ratios appear to be more variable than in other ecosystems worldwide. The human impact on the stoichiometry of these types of ecosystems in estuarine wetlands has received little attention (Koerselman and Meuleman, 1996). The study of the C, N and P concentrations and stoichiometries of wetland soil would be useful for determining the cycles and balances of C, N and P and the fertility of the soil. The current rapid development of the global economy stimulates human disturbance of natural ecosystems and hence their soil C, N and P biochemical processes (Peñuelas et al., 2012, 2013). Anthropogenic inputs of N and P increased from the 1860s to this century to the point that they reached the levels of the natural global N and P fluxes and caused an imbalance of C, N and P stoichiometry that is likely to increase in the near future (Peñuelas et al., 2012, 2013).

Ecological stoichiometric studies in terrestrial ecosystems have mainly focused on N and P (Sardans et al., 2011, 2012a). Recent stoichiometric studies have observed that potassium (K) is even more associated than is N or P with stoichiometric differences among various plant ecotypes (Sardans and Peñuelas, 2014; Sardans et al., 2012c) or with stoichiometric shifts in response to environmental changes (Rivas-Ubach et al., 2012; Sardans et al., 2012c). The strong link between plant K concentrations and water availability (Sardans et al., 2012c; Yavitt et al., 2004) justifies the study of K and its stoichiometric relationships with other nutrients. This focus would more strongly integrate the dimension of water availability in the study of terrestrial ecological stoichiometry and would better characterize biogeochemical niches. Recent ecological stoichiometric studies have observed that K plays a more fundamental role than does N or P in the differences in elemental composition between and within species, depending on the environmental conditions of growth, especially those related to water availability (Lawniczak et al., 2009; Sardans et al., 2012c).

Because of the intensity of local-scale disturbances, both horizontal and vertical heterogeneity will change the elemental composition of soil. A better knowledge of the resulting soil C, N and P ecological stoichiometries would provide decision makers with the necessary information for developing effective methods to enhance the potential capacity of soil to fix C and reduce the emissions of greenhouse gases (Peñuelas et al., 2013).

China has a coastal zone approximately 18, 000 km in length, much of which is occupied by tidal wetlands in estuaries, estimated at more than 1.2×10^4 km^2 (Huang et al., 2006; Shen and Zhu, 1999). These areas are characterized by rapid economic development, and the intensity of human disturbance is higher than in other ecosystems, with much replacement of natural undisturbed areas by areas disturbed by crops, livestock, pollution and tourism. N and P loads to rivers caused by human activities and further transported by upstream rivers to the wetlands (Howarth et al., 1996) cause water eutrophication (Anderson et al., 2002), which threatens the health of wetlands (An et al., 2007) and decreases ecosystem services (Lee et al., 2006). Research, however, has been scarce, and studies are therefore needed on different spatial and temporal scales.

To further understand the effects of human disturbances on soil C, N, P and K concentrations and stoichiometries in wetlands, we here aimed to: (1) clarify the changes in soil C, N, P and K concentrations associated with human disturbance and determine the relationships among C, N, P and K concentrations at different soil depths in estuarine tidal wetlands, (2) explore the influencing factors and (3) discuss the relationships between the C:nutrient, N:P, N:K and P:K ratios and the capacity of soil to fix C.

2. Material and methods

2.1. Study area

This study was conducted in the Shanyutan wetland (26°01′46″N, 119°37′31″E; Fig. 1), the largest tidal wetland (approximately 3120 ha) in the Minjiang River estuary. The climate in this region is relatively warm and wet with a mean annual temperature of 19.6 °C and a mean annual precipitation of 1346 mm (Zheng et al., 2006). The soil surface across the study site is submerged beneath 10–120 cm of water for 3–3.5 h during each tidal inundation. At low tide, soil surfaces of the entire estuarine wetland are exposed, and the annual average weight of the water content (ratio of water weight to dry-soil weight) and the soil redox potential are 116% and 12.6 mV, respectively. The soil remains flooded at some depths. The average salinity of the tidal water from May to December 2007 is 4.2 ± 2.5‰. *Phragmites australis* is one of the most important plant species (Liu et al., 2006) in the area and is typically found in the upper (mid to high) portions of mudflats, which are a main component of the Shanyutan tidal wetland.

P. australis is a C_3 plant (mature height of 2 m with 150 stems m^{-2}). The above- and belowground biomasses of *P. australis* in the study area are 1500 and 2322 g m^{-2}, respectively, and the above- and belowground C, N and P storages by the plants are 0.24 and 0.85 kg m^{-2}, 16.7 and 21.8 g m^{-2} and 0.60 and 1.97 g m^{-2}, respectively (Tong et al., 2011). The rate of decomposition of litter from these plants is 0.00384 d^{-1}, and the amounts of C, N and P released account for 53.1, 79.6 and 79.1%, respectively, of the initial litter during the 280-day period of decomposition (Wang et al., 2012a).

The areas of natural wetlands are gradually decreasing as human disturbance increases. We have studied the following types of human disturbance: (1) natural *P. australis* wetland with very limited or no human disturbance was defined as the control, (2) grassland established in *P. australis* wetlands where cattle have been bred for six years, (3) mudflats where mudskippers have been bred for 10 years (hereafter referred to as flat breeding), (4) pond aquaculture where fish have been bred for 10 years and (5) cropland where rice has been cultivated for 70 years was defined as very high disturbance; the rice cropland received annual applications of N, P and K fertilizers at 95, 30 and 58 kg ha^{-1}, respectively (Wang et al., 2012b).

2.2. Soil-sample collection and measurement

The soil samples were collected in October 2007. Sampling locations were established in the *P. australis* wetland, grassland, flat breeding, pond aquaculture and rice cropland (Fig. 1). Three plots were randomly selected in each of the locations, and soil profiles (width, 1 m; length, 1 m; depth, 0.5 m) were excavated. Samples were collected with a small sampler (length and diameter were 0.3 and 0.1 m) from each of five soil layers (0–10, 10–20, 20–30, 30–40 and 40–50 cm) at the center and both sides of the soil pit. These three samples from each layer were bulked to form one sample per layer. A total of 75 soil samples (five types of land-use × three plots × five soil layers) were thus collected. In the laboratory, the soil samples were air-dried, roots and visible plant remains were removed and the soil samples were finely ground in a ball mill.

Total soil organic C was determined by the $K_2Cr_2O_7$–H_2SO_4 digestion method (Bai et al., 2005; Sorrell et al., 1997), total soil N concentration was analyzed by the K 370 Kjeldahl method (Buchi Scientific Instruments, Switzerland), total soil P concentration was measured by perchloric-acid digestion followed by ammonium-molybdate colorimetry, available-P concentration was determined by extraction with acidic ammonium fluoride and measurement using an UV-2450 spectrophotometer (Shimadzu Scientific Instruments, Japan), total K concentration was determined by FP 640 flame photometry (Shanghai Electronic Technology Instruments, China) and available-N concentration was measured by the alkaline-hydrolysis diffusion method (Lu, 1999).