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Soil moisture and texture primarily control the soil nutrient stoichiometry across the Tibetan grassland

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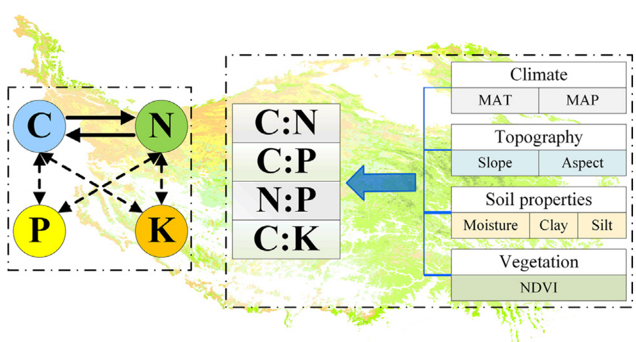
HIGHLIGHTS

- Permafrost does not impact topsoil nutrient stoichiometry in Tibetan grassland.
- Carbon and nitrogen decouple from phosphorus and potassium in alpine soils.
- Soil moisture, texture, and vegetation mainly control topsoil nutrient stoichiometry.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil nutrient stoichiometry and its environmental controllers play vital roles in understanding soil-plant interaction and nutrient cycling under a changing environment, while they remain poorly understood in alpine grassland due to lack of systematic field investigations. We examined the patterns and controls of soil nutrients stoichiometry for the top 10 cm soils across the Tibetan ecosystems. Soil nutrient stoichiometry varied substantially among vegetation types. Alpine swamp meadow had larger topsoil C:N, C:P, N:P, and C:K ratios compared to the alpine meadow, alpine steppe, and alpine desert. In addition, the presence or absence of permafrost did not significantly impact soil nutrient stoichiometry in Tibetan grassland. Moreover, clay and silt contents explained approximately 32.5% of the total variation in soil C:N ratio. Climate, topography, soil properties, and vegetation combined to explain 10.3–13.2% for the stoichiometry of soil C:P, N:P, and C:K. Furthermore, soil C and N were

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weakly related to P and K in alpine grassland. These results indicated that the nutrient limitation in alpine ecosystem might shifts from N-limited to P-limited or K-limited due to the increase of N deposition and decrease of soil P and K contents under the changing climate conditions and weathering stages. Finally, we suggested that soil moisture and mud content could be good predictors of topsoil nutrient stoichiometry in Tibetan grassland.

1. Introduction

In general, elemental stoichiometry reflects the interactions between plants, soil, and microbes, and links biogeochemical patterns to physiological constraints (Sterner and Elser, 2002), which is a predominant driver of nutrient cycling and is also a strong predictor of bacterial diversity and nutrient limitation (Delgado-Baquerizo et al., 2017). Moreover, high-latitude/altitude ecosystems could alter the carbon (C) and nutrient cycling due to the potential feedback to climate change (Schuur et al., 2015). Therefore, investigating the patterns and environmental controllers of soil nutrient stoichiometry in alpine grassland could increase our understanding of nutrient cycling under the changing environmental conditions.

The C, nitrogen (N), and phosphorus (P) cycles are closely coupled through organic matter decomposition and ecosystem respiration due to the constrained proportions of these elements required by organisms (Finzi et al., 2011; Mooshammer et al., 2017). On regional to global scales, plants, soil microbial communities, and topsoil had strict C:N:P ratios (Xu et al., 2013). In contrast, rapid climate change and human activities could cause the imbalance of nutrient interactions (Sardans et al., 2012; Delgado-Baquerizo et al., 2013; Williamson et al., 2016), altering nutrient cycling. Warming and frequent freeze-thaw cycles could also reduce the coupling of C:N:P among different ecosystems (Mooshammer et al., 2017). C and N decoupled from P in an extremely arid environment, inhibiting plant and microbial activity (Delgado-Baquerizo et al., 2013). Furthermore, increased nutrient stoichiometry in plants leaf, litter or mineral soils might constrain microbial decomposition and result in the nutrient limitation in the ecosystem (Sardans et al., 2012). However, the flexibility and interactions of soil nutrients still remain poorly understood in alpine grassland.

Nutrient stoichiometry (C:N:P ratio) was significantly influenced by ecosystem types, land use types, soil types, and environmental gradients (He et al., 2006, 2008; Chen et al., 2016). Xu et al. (2013) observed that wetland and tundra had the largest microbial C:N:P ratios. Reich and Oleksyn (2004) observed that leaf and root N:P significantly reduced with increasing latitude on a global scale. Xu et al. (2013) and Chen et al. (2016) ascertained that microbial C:N:P stoichiometry is significantly related to latitude, temperature, precipitation, microbial community, and soil pH. However, those studies primarily focused on the stoichiometry of plants, microbial biomass, and macronutrients and their controlling factors, while little information is known regarding the influence of topographic and edaphic variables on nutrient stoichiometry in soils. Moreover, role of potassium (K), the third major element after N and P for plant production, has mostly been neglected in estimating the responses of climate change to terrestrial biogeochemical cycles (Sardans and Peñuelas, 2015). Furthermore, high spatial heterogeneity of soil nutrients combined with limitations of observations lead to large uncertainties when investigating regional variations in soil nutrient stoichiometry (Xu et al., 2013; Chen et al., 2016). Therefore, the systematic investigation could help to advance our understanding the controlling factors of soil nutrient stoichiometry on a large scale.

The Tibetan permafrost has been degraded over recent years (Zhao et al., 2010). This process could affect ecological and hydrological processes, resulting in considerable loss of soil nutrients and altering the nutrient cycling (Yang et al., 2010). In addition, over the Tibetan Plateau, soil nutrients are significantly influenced by vegetation types through soil moisture and texture (Wu et al., 2016; Tian et al., 2017). However, limited studies investigated the broad-scale patterns of soil nutrient stoichiometry in the Tibetan grassland, and whether they are affected by permafrost conditions. In this study, we examined the patterns and influencing factors of soil nutrient stoichiometry in the alpine grassland of the Tibetan Plateau. Specifically, we hypothesized that: (1) soil nutrient stoichiometry is lower in alpine desert than that in alpine swamp meadow due to better environmental conditions in alpine swamp meadow (i.e. soil moisture, soil texture, soil pH, and soil nutrients; Tian et al., 2017); (2) the controlling factors of soil nutrient stoichiometry might differ across vegetation types because soil nutrients under different vegetation types are controlled by different environmental factors (Tian et al., 2017); (3) soil nutrients might decouple in alpine grassland due to the different degrees of biological and geochemical processes that control the supply of soil elements (e.g. C and N are mainly related to biological processes, while P and K are primarily controlled by rock weathering; Whitehead, 2000; Delgado-Baquerizo et al., 2013). To test these hypotheses, data on soil nutrients were collected from 185 sites across the Tibetan grassland.

2. Materials and methods

2.1. Study area description

The Tibetan Plateau has a permafrost area of 1.06×10^6 km^2, occupying 40% of the plateau area (Fig. 1; Zou et al., 2017). The long-term and spatially averaged active layer thickness ranged from 1.32 to 4.57 m (Pang et al., 2009). The mean annual temperature (MAT) and precipitation (MAP) varied from −9.7 to 6.8 °C and from 84 to 700 mm over the Tibetan Plateau, respectively (Chen et al., 2016; Ding et al., 2016). Climate warming has also been happened during the last fifty years on the plateau, with an increasing rate ranging of 0.02–0.04 °C/yr (Yang et al., 2017).

The prevailing vegetation types are alpine swamp meadow, alpine meadow, alpine steppe, and alpine desert. Alpine swamp meadow is mainly distributed in the low-lying zones with the dominant species of *Kobresia tibetica* (Tian et al., 2017). Alpine meadow is distributed in wet regions, dominated by *Kobresia pygmaea* and *Kobresia humilis* (Tian et al., 2017). Alpine steppe is dominated by *Stipa purpurea* (Tian et al., 2017). Alpine desert occurs in arid regions with the dominant species of *Carex moorcroftii* (Wu et al., 2016). There are five soil orders in Tibetan permafrost: Gelisols (34%), Inceptisols (28%), Mollisols (14%), Aridisols (13%), and Entisols (11%; Li et al., 2015). Soil parent materials contain alluvial, fluvial, and lacustrine deposits (Fang et al., 2015).

2.2. Soil sampling and analyses

We sampled 185 sites (Fig. 1) throughout the Tibetan grassland between mid-August and mid-October of 2009–2011 when the active layer is almost completely thawed (Zhao et al., 2000). Of those 185 sites, 18 were from alpine swamp meadow, 62 from alpine meadow, 54 from alpine steppe, and 51 from alpine desert. These sampling sites covered the typical vegetation types and permafrost conditions, and could be representative of the eastern, central, and western parts of the plateau. For each site, due to the possible great heterogeneity in soil properties, several samples were mixed as one composite sample