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Spatially-explicit estimate of soil nitrogen stock and its implication for land model across Tibetan alpine permafrost region

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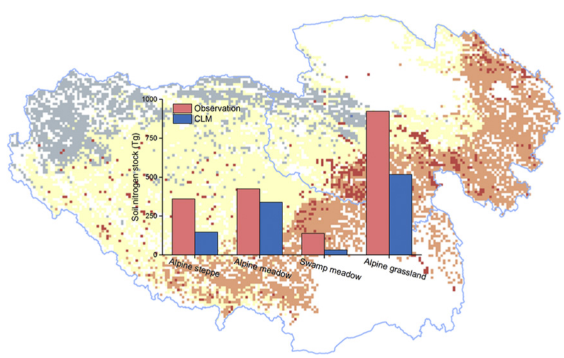
HIGHLIGHTS

- 1802 Tg nitrogen was stored in the 0–3 m depth across the Tibetan alpine permafrost region.
- CLM underestimated the nitrogen stock across the Tibetan alpine permafrost region.
- Biological nitrogen fixation process played a key role in the model underestimation.

GRAPHICAL ABSTRACT



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ABSTRACT

Permafrost soils store a large amount of nitrogen (N) which could be activated under the continuous climate warming. However, compared with carbon (C) stock, little is known about the size and spatial distribution of permafrost N stock. By combining measurements from 519 pedons with two machine learning models (supporting vector machine (SVM) and random forest (RF)), we estimated the size and spatial distribution of N stock across the Tibetan alpine permafrost region. We then compared these spatially-explicit N estimates with simulated N stocks from the Community Land Model (CLM). We found that N density (N amount per area) in the top three meters was 1.58 kg N m^{-2} (interquartile range: 1.40–1.76) across the study area, constituting a total of 1802 Tg N (interquartile range: 1605–2008), decreasing from the southeast to the northwest of the plateau. N stored below 1 m accounted for 48% of the total N stock in the top three meters. CLM4.5 significantly underestimated the N stock on the Tibetan Plateau, primarily in areas with arid/semi-arid climate. The process of biological N fixation played a key role in the underestimation of N stock prediction. Overall, our study highlights that it is imperative to improve the simulation of N processes and permafrost N stocks in land models to better predict ecological consequences induced by rapid and widespread permafrost degradation.

1. Introduction

Permafrost regions, mainly distributed in cold areas with high latitude or high altitude, cover approximately 23.9% of the Northern

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Hemisphere (Zhang et al., 1999). These regions have accumulated substantial soil organic matter due to slow decomposition in cold and wet environments (Hugelius et al., 2014; Strauss et al., 2013; Tarnocai et al., 2009). However, climate warming is rapidly exposing permafrost soil organic matter to microbial decomposition, potentially producing a large amount of carbon (C) dioxide from permafost regions (Schädel et al., 2016; Schuur et al., 2009, 2015). Permafrost thaw is also expected to accelerate the depolymerization and mineralization of soil organic nitrogen (N), potentially releasing dissolved organic and inorganic N and increasing soil N availability (Beermann et al., 2017; Harms et al., 2014; Keuper et al., 2012; Natali et al., 2012). An increase of available N could fundamentally alter many key ecosystem processes, such as plant production (Keuper et al., 2017; Natali et al., 2012), gaseous losses (Abbott and Jones, 2015; Elberling et al., 2010; Marushchak et al., 2011; Repo et al., 2009) and leaching of dissolved N (Abbott et al., 2015; Frey et al., 2007; Harms and Jones, 2012; Treat et al., 2016), which could dramatically influence the interactions among permafrost ecosystems, the C cycle and global climate (Chapin et al., 2011). Consequently, it is crucial to evaluate the size and spatial distribution of N stocks in permafrost regions to accurately predict the alteration of ecosystem N cycle and its ecological consequences under permafrost thaw.

At present, our knowledge of soil N stock in permafrost regions mainly comes from two sources: soil N stock evaluation at the global scale which covers the permafrost extent (*e.g.*, Batjes, 1996, 2016; Post et al., 1985) or soil N stock assessment at local scale within the permafrost region (*e.g.*, Zubrzycki et al., 2013). These studies have improved our understanding of soil N stock in permafrost regions, however, several limitations still exist. First, spatial pattern of soil N stock across the permafrost area is still inexplicit (Kaiser et al., 2005; Rodionov et al., 2007). The inexplicit spatial distribution is associated with the simple but commonly used thematic mean upscaling approach, limited sample size, and uneven distribution of sampling sites in permafrost regions (Beer et al., 2010; Ding et al., 2016). Initially, only 58 sites were used to evaluate soil N stock in tundra around the world (Post et al., 1985). With the increasing attention on this issue, the sample size derived from permafrost regions has been extended to 682 profiles in a recent global assessment by Batjes (2016), but it is still admittedly inadequate for spatially-explicit N estimates given the vast area and heterogeneous landscape (Mishra et al., 2013). Second, deep soil N stock in permafrost regions is largely unknown. Under global warming scenario, deep soil N is of high significance since permafrost thaw could affect the entire soil profile (Harden et al., 2012; Koven et al., 2015). However, current studies concentrate on the top one-meter depth (*e.g.*, Post et al., 1985; Tian et al., 2006; Yang et al., 2007; Zubrzycki et al., 2013), which greatly limits our understanding of deep soil N cycle.

Exploring the fate of permafrost N after thaw has been identified as a major research priority among global change research community (Abbott et al., 2016). A first step towards this goal is improving spatially-explicit estimates of permafrost N stock with more data and more-advanced approaches such as machine learning. These estimates could then be used to evaluate the performance of coupled ecosystem models, one of the major tools in predicting the fate of ecosystem N cycle after permafrost thaw (Harden et al., 2012; Koven et al., 2015). Community Land Model (CLM) is a widely used land model that incorporates a full N cycle, and it has been frequently used to simulate ecosystem dynamics in permafrost regions (Koven et al., 2013; Lawrence et al., 2008; Swenson et al., 2012). With the CLM version 4.5 (CLM4.5) (Oleson et al., 2013), a recent study demonstrated that permafrost thaw stimulated soil N mineralization, which could relieve nutrient limitation for plant growth and thus offset a portion of C losses from permafrost soils (Koven et al., 2015). This pioneering work provided the first attempt to explore C-N interactions in permafrost regions, but permafrost N dynamics derived from CLM4.5 remain incomplete and highly uncertain (Koven et al., 2015). It is thus essential to diagnose the N cycle in CLM4.5 by evaluating the model performance with empirical N stocks so that we could further improve the model. However, current data-model comparison studies concentrate on permafrost C simulations (Carvalhais et al., 2014; Yan et al., 2014; Xia et al., 2017), with limited evaluation for model performance in permafrost N cycle.

The Tibetan Plateau is the largest high-altitude permafrost region on Earth (Zhang et al., 1999). Similar to Arctic area, the plateau has also experienced significant climate warming and extensive permafrost degradation (Wang et al., 2008; M. Yang et al., 2010). These environmental changes could accelerate the mineralization of soil organic N, and further affect the interaction of permafrost ecosystems with atmospheric and aquatic systems by altering soil N availability. However, the estimation of spatially-explicit soil N stock to three-meter depth and the evaluation of land model performance in simulating N stock across the Tibetan alpine permafrost region are still lacking. To fill these knowledge gaps, we collected 342 three-meter cores and 177 fifty-centimeter pits across 173 sampling sites on the Tibetan Plateau during the summer of 2013 and 2014. Based on these site-level measurements and two machine learning models (supporting vector machine (SVM) and random forest (RF)), we aimed to answer the following two questions: 1) What is the size of permafrost N stock at three-meter depth on the Tibetan Plateau? 2) How realistically does CLM4.5 represent the N stock on the plateau?

2. Materials and methods

2.1. Study area

The Tibetan Plateau, known as "the world's third pole", has an average altitude higher than 4000 m, with 67% of its area underlain by permafrost (Zhang et al., 1999). The average thickness of the active layer is approximately 2.4 m, varying between 1.3 and 4.6 m along the Qinghai-Tibet railway (Wu and Zhang, 2010). During the past several decades, the plateau has experienced rapid top-down permafrost thaw as well as thermokarst due to sustained climate warming (Mu et al., 2017; Wu and Zhang, 2010; Yang et al., 2018a, 2018b). Alpine grassland is the most widely distributed vegetation type across the study area, including alpine steppe, alpine meadow and swamp meadow (Editorial Committee for Vegetation Map of China, 2001). The dominant species among the three grassland types are *Stipa purpurea* and *Carex moorcroftii*; *Kobresia pygmaea* and *K. humilis*; and *K. tibetica*, respectively (Yang, 2008; Zhang et al., 1988).

2.2. Soil sampling

To evaluate the permafrost N stock on the Tibetan Plateau, we investigated 173 sites during the maximum growing season (July or August) of 2013 and 2014 (Ding et al., 2016). The field campaign was conducted along the major roads across the plateau due to the traffic inaccessibility and extreme climatic conditions (Y. Yang et al., 2010). Nonetheless, the 173 sampling sites, ranging from 80.8° E to 101.7° E and from 29.3° N to 37.8° N, covered broad climate gradients and all major grassland/soil types on the plateau (Fig. S1). Moreover, ratio of the sample size in each grassland type (91 in alpine steppe, 75 in alpine meadow and 7 in swamp meadow) roughly followed the areal distribution of these grassland types on the Tibetan Plateau (91:64:7) (Table 1). In addition, to better represent the spatial heterogeneity of N stock in swamp meadow, we also included data from 36 profiles at 12 field sites presented in Yang (2008) (Fig. S1). Collectively, these sampling sites could be expected to be representative for the permafrost N estimation on the Tibetan plateau.

At each of the 173 sampling sites, a 10 m × 10 m plot was set up; then, five 1 m × 1 m quadrats were established at the corners and center of the plot (Ding et al., 2016). Soil samples were collected at the center of the three 1 m × 1 m quadrats along a diagonal line. Consequently, 519 pedons were collected from the 173 sites. Among them, 342 pedons in 114 sites were collected down to a three-meter depth