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# Response of alpine soils to nitrogen addition on the Tibetan Plateau: A meta-analysis

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ABSTRACT

A meta-analysis approach was used to identify general tendency of alpine soil responses to nitrogen fertilizer on the Tibetan Plateau. Nitrogen addition increased ammonium nitrogen ($NH_4^+$) and nitrate nitrogen ($NO_3^-$), but decreased pH. Effects of nitrogen addition on soil organic carbon (SOC), total nitrogen (TN), C:N ratio and pH differed among forests, alpine meadows and alpine steppes. Effects of nitrogen addition on $NH_4^+$, $NO_3^-$, soil microbial biomass carbon (MBC) and nitrogen (MBN) differed between alpine meadows and forests. Effects of $NH_4NO_3$ addition on SOC, TN, C:N ratio, $NH_4^+$, $NO_3^-$, MBC and pH differed with those of urea addition. The effect of nitrogen addition on pH was negatively correlated with mean annual temperature and mean annual precipitation. Soil conditions in control plots were positively correlated with the effect of nitrogen addition on pH, but negatively correlated with the effect of nitrogen addition on TN. Nitrogen addition rate was correlated with the effect of nitrogen fertilizer on $NO_3^-$ and pH. Nitrogen addition duration was positively correlated with the effect of nitrogen fertilizer on pH. Therefore, effects of nitrogen fertilizers on alpine soils varied with nitrogen fertilizer types; climatic warming and precipitation change regulated effects of nitrogen fertilizer on alpine soils; and response of alpine soils to nitrogen addition may depend on initial soil conditions, rate and duration of nitrogen addition on the Tibetan Plateau.

## 1. Introduction

Fertilizer applications play vital roles in maintaining nutrient balance in terrestrial ecosystem, generally increase soil nutrient and stimulate plant growth and biomass accumulation (Fu and Shen, 2016; Wang et al., 2010). Based on this, fertilizations are often used as crucial measures in terrestrial ecosystem managements, such as degraded grasslands restoration and agricultural production (Valkama et al., 2009; Wang et al., 2013). Owing to such fertilizations, especially inorganic fertilizer applications, global carbon and nitrogen cycling has been greatly changed (Lu et al., 2011a; Tian et al., 2014). For example, nitrogen addition increases soil inorganic nitrogen leaching by 461%, nitrate nitrogen ($NO_3^-$) by 429%, nitrification by 154%, nitrous oxide emission by 134%, denitrification by 84% (Lu et al., 2011a), and aboveground litter production by 20% (Liu and Greaver, 2010) at global scale, but decreases species richness by 11.2% on the Tibetan Plateau (Fu and Shen, 2016). With the increase in nitrogen fertilizer application, global nitrogen deposition inputs to terrestrial ecosystems has greatly increased (Lamarque et al., 2005).

Nitrogen fertilizer is one of the most common inorganic fertilizers (Valkama et al., 2009). Although many meta-analyses quantitatively analyzed the general tendency of plant, soil and ecosystem to nitrogen addition at global or regional scale (e.g. Dormann and Woodin, 2002; Garcia-Palacios et al., 2015; LeBauer and Treseder, 2008; Yandjian et al., 2011), several uncertainties remain regarding the general nitrogen enrichment effects on soils. First, the effect of nitrogen addition on soil carbon was observed to be positive (Bouskill et al., 2014; Lu et al., 2011b), or negligible (Sillen and Dieleman, 2012). Second, there were inconsistent general tendencies of soil microbial biomass to nitrogen addition, with no change (Bouskill et al., 2014) or decrease (Lu et al., 2011a; Treseder, 2008). In contrast, nitrogen addition increased soil microbial biomass in a desert soil (Zhou et al., 2012), a semi-arid temperate steppe soil (Zhang et al., 2008) and an alpine tundra soil (Fisk and Schmidt, 1996). Third, the correlation between nitrogen addition rate and the effect of nitrogen addition on soil microbial biomass was negative (Bouskill et al., 2014) or negligible (Lu et al., 2011a; Treseder, 2008), indicating that whether the nitrogen

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addition rate can affect the response of soils to nitrogen addition is uncertain.

The Tibetan Plateau is one of the most sensitive regions to global change and alpine ecosystems on the Tibetan Plateau are typical and important components of the global alpine terrestrial ecosystems (Fu et al., 2015a; IPCC, 2013), whereas results from many of the inorganic fertilizers experiments in alpine ecosystems on the Tibetan Plateau have not been included in previous global meta-analyses (Fu and Shen, 2016; Fu et al., 2015b). Nitrogen are key limiting factors in alpine ecosystems on the Tibetan Plateau (Fu and Shen, 2016; Jiang et al., 2013). To examine responses of alpine soils to nitrogen addition, many field nitrogen fertilizer experiments were conducted on the Tibetan Plateau (Fu and Shen, 2016). A synthesis of the effect of nitrogen addition on alpine soils data is still lacking on the Tibetan Plateau, indicating that the general responses of alpine soils to nitrogen addition remains unclear on the Tibetan Plateau. Therefore, we compiled 314 data from nitrogen addition studies on the Tibetan Plateau. The main objectives of this study were to (1) quantitatively identify the general tendencies of alpine soils responses; and (2) examine the correlations between the effects of nitrogen addition on alpine soils and nitrogen addition rate, nitrogen addition duration, mean annual temperature, mean annual precipitation and soil conditions in control plots on the “Earth’s Third Pole”.

## 2. Materials and methods

### 2.1. Data compilation

Articles published before June 2015 were searched using the Web of Science and the China National Knowledge Infrastructure (Supporting information, Table S1). The compiled database included soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), ratio of carbon to nitrogen (C:N ratio), ammonium nitrogen ($NH_4^+$), nitrate nitrogen ($NO_3^-$), available phosphorus (AP), microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), pH and dissolved organic carbon (DOC).

The criteria were (1) only data from the control and nitrogen addition treatments were adopted for multifactor experiments; (2) only the latest results were included for multiple measurements over time; (3) only field studies performed in alpine ecosystems on the Tibetan Plateau were used (Fig. 1); (4) at least one of the concerned variables mentioned above were measured; (5) means, standard deviations (or standard errors), and numbers of replication were directly provided or could be calculated; and (6) multiple soil depths, nitrogen addition rates, nitrogen addition types, or ecosystem types were treated as independent.

Mean annual temperature (−3 to 8.9 °C), mean annual precipitation (412–920 mm), nitrogen addition rate (10–350 kg N $hm^{-2}\,a^{-1}$), nitrogen addition duration (0–8 year) and the response variables were collected. Vegetation types included forests, alpine meadows and alpine steppes. Nitrogen fertilizers included urea, ammonium nitrate, ammonium sulfate, potassium nitrate, sodium nitrate and ammonium chloride. We extracted the data of the response variables using the GetData software if the studies provided these data in figures (Fu et al., 2015a; Shen et al., 2015).

### 2.2. Statistical analyses

Our meta-analysis was performed using the METAWIN 2.1 software (Sinauer Associates Inc., Sunderland, MA, USA). We used a fixed effects model to examine whether a specific variable had a significant response to nitrogen addition (Rosenberg et al., 2000). The effect of nitrogen addition on each variable was statistically significant if the 95% bootstrap CI did not cover zero (Wan et al., 2001). A fixed effects model with a grouping variable was performed to test whether there were significant differences on a specific variable among forests, alpine meadows and alpine steppes, and between $NH_4NO_3$ addition and urea addition (Rosenberg et al., 2000). A random effects model with a continuous variable (>30 observations) was used to examine the correlations between effect sizes of nitrogen addition and nitrogen addition rate, nitrogen addition duration, mean annual temperature, mean annual precipitation and soil conditions in control plots (Rosenberg et al., 2000).

We used the natural logarithm of response ratio ($R$) as effect size and the inverse of pooled variance ($1/v$) as weighting factor ($w$) (Hedges et al., 1999),

$$\ln R = \ln\left(\frac{\overline{X_t}}{\overline{X_c}}\right) = \ln(\overline{X_t}) - \ln(\overline{X_c}) \tag{1}$$

$$v = \frac{S_t^2}{n_t \overline{X_t^2}} + \frac{S_c^2}{n_c \overline{X_c^2}} \tag{2}$$

where $\overline{X_c}$ and $\overline{X_t}$ are mean values in control and nitrogen addition groups, respectively; $S_c^2$ and $S_t^2$ are standard deviations in control and nitrogen addition groups, respectively; $n_c$ and $n_t$ are numbers of replication in control and nitrogen addition, respectively.

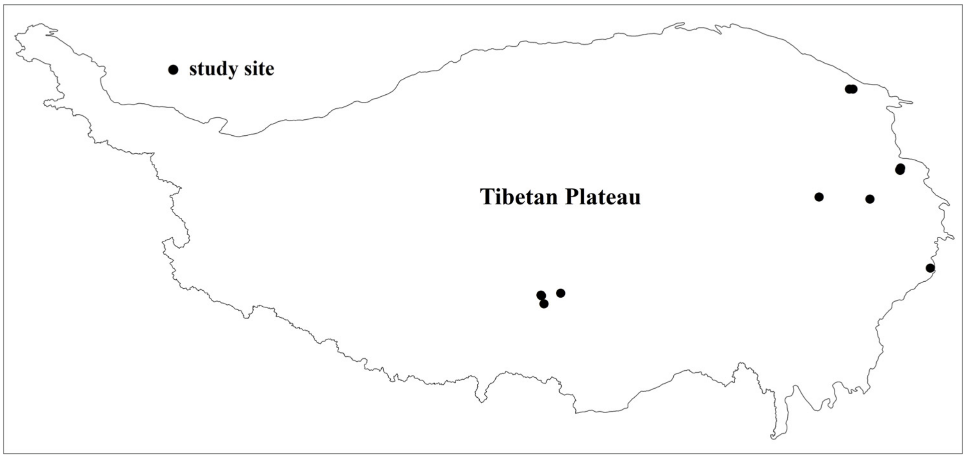

**Fig. 1.** Study sites from a meta-analysis of nitrogen addition on alpine soils on the Tibetan Plateau.