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# A meta-analysis of the effects of experimental warming on soil carbon and nitrogen dynamics on the Tibetan Plateau

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ABSTRACT

Alpine ecosystems at high altitudes and latitudes are notably sensitive to climatic warming and the Tibetan Plateau is a widely distributed alpine ecosystem. The magnitude of climatic warming on the Tibetan Plateau is expected to be considerably greater than the global average. However, a synthesis of the experimental warming soil carbon and nitrogen data is still lacking and whether forest soils are more sensitive to warming than grassland soils remains unclear. In this study, we used a meta-analysis approach to synthesise 196 observations from 25 published studies on the Tibetan Plateau. Warming significantly increased microbial biomass carbon (MBC) by 14.3% (95% CI: 2.9–24.6%), microbial biomass nitrogen (MBN) by 20.1% (95% CI: 2.0–45.1%), net nitrogen mineralization by 49.2% (95% CI: 38.1–62.3%) and net nitrification by 56.0% (95% CI: 51.4–66.1%), but did not significantly affect soil carbon (95% CI: −13.9 to 2.7%) or nitrogen (95% CI: −12.4 to 2.6%). The mean annual air temperature was negatively correlated with the warming effects on MBC and MBN. Grasslands exhibited significant MBC and MBN responses to warming. Specifically, soil microbial biomass was more responsive to warming in colder environments. Moreover, forest soils are not always more sensitive to warming than grassland soils as previous studies have suggested. These findings indicate that clarifying the effect of warming on alpine soils need consider ecosystem types and their local climate.



## 1. Introduction

Alpine ecosystems at high altitudes and latitudes are notably sensitive to climatic change, although there are many uncertainties in how these systems will respond to climatic change (IPCC, 2007; Shen et al., 2014). The Tibetan Plateau, a widely distributed alpine ecosystem, is one of the most sensitive regions to global climatic change worldwide (Chen et al., 2013; Fu et al. in press; Miehe et al., 2011; Zhang et al., 2000). The magnitude of warming in alpine regions is predicted to be much greater than the global average (IPCC, 2007). The warming amplitude increases with increasing altitude on this Plateau (Liu and Chen 2000; Yao et al., 2000). Field experiments have analysed the potential effects of warming on the alpine soils on the Tibetan Plateau (Fu et al., 2012; Li et al., 2011; Rui et al., 2011; Xu et al., 2010a; Yu et al., 2014). However, a synthesis of the experimental warming data is still unavailable and thus, the general tendency of the warming effects remains unclear for alpine soils across this Plateau.

The microbial biomass of carbon (MBC) and nitrogen (MBN) in soil are important components in terrestrial ecosystem carbon and nitrogen cycling and serve as sources (mineralization) or sinks (immobilisation) of labile carbon and nitrogen pools (Bai et al., 2013; Lu et al., 2013a). The microbial biomass in soil responds quickly to changes in the soil temperature (Alvarez et al., 1995). MBC is likely to be more responsive to warming than MBN across all terrestrial ecosystems (Bai et al., 2013; Lu et al., 2013a). The non-significant response of MBN to warming may result from the limited availability of carbon sources (Bai et al., 2013), while warming significantly increases the dissolved organic carbon (DOC), an important carbon source for soil microorganisms (Lu et al., 2013a). Therefore, the underlying mechanism causing the non-significant effect that warming has on MBN remains unclear.

Both the increase in soil respiration ($R_s$) (Lin et al., 2011b; Lu et al., 2013b; Shi et al., 2012; Xiong et al., 2010; Xu et al., 2010b) and the decline in litter quantity (Li et al., 2011; Lin et al., 2011a; Luo et al., 2009) contribute to the decrease in the soil carbon and nitrogen pools on the Tibetan Plateau. The increase in MBC caused

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by warming also implies that warming may accelerate organic matter decomposition in soil (Wang et al., 2011), while inconsistent responses of MBC and MBN to warming have been reported on this Plateau (Chen et al., 2010; Fu et al., 2012; Wang et al., 2011). Warming-induced increases in the net nitrogen mineralization and nitrification rates increased the nitrogen availability in soil (Bai et al., 2013; Rustad et al., 2001), which in turn increased plant biomass accumulation (Fu et al., in press; Rustad et al., 2001) and soil microbial biomass (Yin et al., 2012; Yu et al., 2014). Furthermore, a warming-induced increase in plant biomass may more or less counterbalance the warming-induced increases in $R_s$ and decreases in litter quantity (Lu et al., 2013a). However, the effects of warming on plant biomass were negative (Klein et al., 2007; Yang et al., 2013), positive (Li et al., 2011; Wang et al., 2012) or neutral (Fu et al., 2013) in alpine ecosystems. The variability between these two factors may result in the inconsistent response of soil carbon and nitrogen to warming on the Tibetan Plateau (Chen et al., 2010; Shi et al., 2012; Wang et al., 2011).

Forests show stronger responses to warming than grasslands in terms of soil respiration and soil nitrogen availability (Bai et al., 2013; Lu et al., 2013a; Rustad et al., 2001), which may be related to the fact that most observations in forests were conducted in more temperature-limited areas (Bai et al., 2013). However, grasslands may generally have lower air temperatures than forests in alpine regions on the Tibetan Plateau (Luo et al., 2010; Shen et al., 2014; Yin et al., 2013). Therefore, it remains unclear whether forests are always more sensitive to warming than grasslands in alpine regions.

In this study, we compiled data from 25 published experimental warming studies across the Tibetan Plateau. The goal was (1) to identify quantitatively the general tendencies caused by warming effects on 18 variables related to the soil carbon and nitrogen pools

**Table 1**
Site characteristics and response variables from a meta-analysis of 25 studies on the Tibetan Plateau.

| Site | Latitude | Longitude | Altitude (m) | MAT (°C) | MAP (mm) | Response variables | References |
|---|---|---|---|---|---|---|---|
| Damxung grassland station | 30.50 | 91.07 | 4300 | 1.3 | 476.8 | MBC, MBN | Fu et al., 2012 |
| Eastern slope of Mount Gongga | 29.83 | 101.88 | 3000 | 3.8 | 1940 | Plant biomass, root length | Yang et al., 2013 |
| Ebao, Qilian County | 37.97 | 100.92 | 3512 | 1 | 409 | Soil C and N, MBC, MBN | Heng, 2011 |
| Fenghuoshan region | 34.73 | 93.07 | 4600–4800 | −5.3 | 269.7 | Soil C and N, MBC, MBN | Li et al., 2010 |
| | | | | | | Soil C and N, MBC, MBN, catalase, urease, protease | Li et al., 2011 |
| Haibei alpine meadow ecosystem research station | 37.62 | 101.20 | 3200 | −2 | 500 | Soil respiration | Lin et al., 2011b |
| | | | | | | Soil N, MBC, MBN, DOC, DON, $NH_4^+$-N and $NO_3^-$-N | Rui et al., 2011 |
| | | | | | | Net N mineralization | Wang et al., 2012 |
| Hongyuan alpine ecosystem research station | 32.45 | 102.37 | 3561 | 1.1 | 752.4 | Polyphenol oxidase, urease | Liu et al., 2011a |
| | | | | | | MBC, MBN | Wang et al., 2011 |
| Kakagou, Songpan County | 32.85 | 103.55 | 3400 | 2.8 | 718 | Soil N, MBC, MBN, net N mineralization, $NH_4^+$-N and $NO_3^-$-N, soil respiration | Shi et al., 2012 |
| | | | | | | Plant biomass | Shi et al., 2010 |
| Maoxian ecological station | 31.68 | 103.88 | 1820 | 8.9 | 920 | Soil C and N, MBC, MBN, $NH_4^+$-N and $NO_3^-$-N | Chen et al., 2010 |
| | | | | | | Soil C and N, MBC, MBN, $NH_4^+$-N and $NO_3^-$-N, root length | Liu et al., 2011b |
| | | | | | | MBC, MBN, $NH_4^+$-N and $NO_3^-$-N, soil respiration | Xiong et al., 2010 |
| | | | | | | Soil C and N, MBC, MBN, net N mineralization and nitrification, $NH_4^+$-N and $NO_3^-$-N, root length | Yin et al., 2012 |
| | | | | | | Net N mineralization, polyphenol oxidase, urease, plant biomass | Yin et al., 2013 |
| Miyaluo experimental forest of Lixian County | 31.58 | 102.58 | 3150 | 8 | 600–1100 | Soil C and N, polyphenol oxidase, catalase, invertase, urease, protease | Pan et al., 2008 |
| | | | | | | Plant biomass | Han et al., 2009 |
| | | | | | | MBC, MBN, DOC, DON, net nitrification, $NH_4^+$-N and $NO_3^-$-N, polyphenol oxidase, catalase, invertase, urease | Xu et al., 2010a |
| | | | | | | Soil C and N, soil respiration | Xu et al., 2010b |
| | | | | | | Net N mineralization, plant biomass | Xu et al., 2012 |
| | | | | | | Plant biomass | Yin et al., 2008a |
| | | | | | | Plant biomass | Yin et al., 2008b |
| Xainza alpine steppe and wetland ecosystem observation and experiment station | 30.95 | 88.7 | 4675 | 0 | 300 | Soil respiration | Lu et al., 2013b |

MBC: soil microbial biomass carbon; MBN: soil microbial biomass nitrogen; DOC: dissolved organic carbon; DON: dissolved organic nitrogen.