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Carbon pools of semi-arid *Picea crassifolia* forests in the Qilian Mountains (north-eastern Tibetan Plateau)

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A B S T R A C T

The vast alpine grasslands of the Tibetan Plateau are lined by a belt of oroboreal coniferous forests in the transition zone to the Central Asian semi-deserts and deserts which may play important roles in the hydrology and biogeochemistry of the region. Many of these forests exist under semi-arid climates, are exposed to rapid climate warming and suffer from intensive human impact. We investigated the carbon stocks in biomass and soil in the *Picea crassifolia* (Qinghai spruce) forests of the Qilian Mountains, north-eastern Tibetan Plateau. In 18 forest plots at 2600–2800 m elevation, we found ecosystem carbon stocks of 348 Mg C ha^{-1} with carbon densities of 43 Mg C ha^{-1} in the live and dead aboveground biomass, 12 Mg C ha^{-1} in roots, 3 Mg C ha^{-1} in litter and 305 Mg C ha^{-1} in the soil (SOC; 0–100 cm). The belowground carbon pools exceed averages reported for northern boreal forests and even more clearly for zonal forest vegetation in the temperate zone. The high SOC density in the *P. crassifolia* forests are probably the result of slow decomposition rates due to low soil temperatures in combination with low soil moisture. The widespread degradation of mountain spruce forests to shrubland reduces the ecosystem carbon stock by >85 Mg C ha^{-1}, and is partly caused by a 15%-reduction in SOC. We conclude that the remaining mountain forests of spruce and other conifers at the northern fringe of the Tibetan Plateau play an important role in the regional carbon budget and need urgent conservation.

1. Introduction

Forests play a key role in the global biogeochemical cycles and in particular in the carbon cycle (Ravindranath and Ostwald, 2008). Estimates suggest that about half of the organic carbon contained in terrestrial ecosystems is stored in forests (IPCC, 2013). The ratio of soil organic carbon (SOC) to biomass carbon tends to increase with increasing latitude (Cao and Woodward, 1998). While much is known about carbon stocks of forests with ample water supply (Houghton, 2005), there is a specific lack of information from forests in semi-arid and arid climates and at high elevations (Luyssaert et al., 2007; Schimel et al., 2011). Although dry forests may harbor a rich and unique biodiversity and provide valuable ecosystem services such as soil water conservation in regions of water shortage, increasing air humidity in local climates, erosion control and the halting of desertification (Malagnoux et al., 2007; le Polain de Waroux and Lambin, 2012; He et al., 2012a), the carbon pools of dry forests are not well studied.

Dry forests are particularly vulnerable to climate warming, wild fires, degradation, and the conversion to grasslands (Allen et al., 2010; Williams et al., 2010). Rising temperatures in the course of climate warming increase the evaporative demand and decrease plant-available soil water (Ma and Fu, 2006; Fellows and Goulden, 2013; Williams et al., 2013). Increased drought stress may lead to reduced tree growth and eventually to increased tree mortality (Rigling et al., 2002; Dulamsuren et al., 2013; Liu et al., 2013). Thus, global warming will most likely reduce the capacity of dry forests to sequester carbon. Another widespread threat to these forests is the degradation to open woodlands and shrubland due to the action of humans and their livestock. Forest degradation due to logging and forest grazing proceed at alarming rates in many regions of semi-arid and arid Central Asia (Kushlin et al., 2004; Lkhagvadorj et al., 2013; Khishigjargal et al., 2014). It is not well known how this degradation process affects the carbon pools in biomass and soil. For a better understanding of the ecosystem services provided by dry forests, it is necessary to quantify the

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carbon losses associated with the transformation of these forests to shrubland.

The Tibetan Plateau, a key area of global change, is dominated by extensive high-elevation grasslands, shrublands and alpine semi-deserts (Cui and Graf, 2009), but there are also significant areas covered with coniferous forests on its north-eastern and south-eastern rims. These forests are the remnants of a large forested area that existed on the Tibetan Plateau in the early and mid Holocene (Herzschuh et al., 2006; Miehe et al., 2008). The forests at the north-eastern rim of the Tibetan Plateau (Qilian Mountains) occur at the drought limit for forests in an area where temperature has recently increased at a rate which exceeds the global average (Liu and Chen, 2000). Model-based climate projections for this region suggest that the local warming trend will proceed, while precipitation is assumed to remain more or less constant (Zhang et al., 2011). Published biomass data and carbon pool assessments for the Tibetan Plateau mainly focus on grasslands (Luo et al., 2002), while corresponding data from forests referred either to the aboveground (Luo et al., 2002; Zhou et al., 2007) or the belowground carbon pools (Yang et al., 2007; Xie et al., 2007), but never analyzed the complete ecosystem carbon pool. Further, a comparison of forest carbon pools with those of forest degradation stages does not yet exist.

Addressing this gap of knowledge, the present study aims at quantifying the major carbon pools of the oroboreal forests of the Qilian Mountains, north-eastern Tibetan Plateau, and to compare these pools with those of adjacent shrubland, which is partly the local climax vegetation, but is in many regions a degradation stage of the forest. We hypothesized that the spruce forests of the north-eastern Tibetan Plateau store relatively large amounts of carbon in the soil, because cold winter temperatures combine with low summer precipitation, thus hampering decomposition. Given the widespread forest destruction in this region, we further aimed to quantify the carbon loss in soil and biomass resulting from the degradation of spruce mountain forest to shrubland.

2. Materials and methods

2.1. Study site

The study was carried out in the Qilian Mountains (Qilian Shan) at the north-eastern edge of the Tibetan Plateau, c. 50 km SW of the city of Zhangye, Gansu Province, China (Fig. 1). The Qilian Mountains form the interface between the alpine *Kobresia* meadows of the Tibetan Plateau in the south, the Gobi Desert in the north and the Chinese Loess Plateau in the east. The dominant tree species is Qinghai spruce (*Picea crassifolia* Kom.), which is mainly found on north-facing mountain slopes between 2600 and 3400 m a.s.l. (Zhao et al., 2006). Trees reach a maximum height of c. 15 m and the reported maximum age is around 400 years (Liang et al., 2010). Below the spruce forest belt, the climate is more arid and the vegetation is dominated by dry shrubland of e.g. *Potentilla fruticosa* L. and *Berberis* spec. South-facing slopes are covered with grasslands. The position of the upper and lower forest lines is modified by human activities and livestock at many places. After the establishment of the Qilian Mountain National Nature Reserve in 1986, forests have been exposed to reduced levels of human disturbance. The Qilian Mountains are located in the transition zone of the influences of the East Asian Monsoon and the Westerlies. The climate is a semi-arid to arid continental mountain climate within the temperate zone with cold and dry winters under the influence of the Mongolian anticyclone. The summers are shaped by the continental low pressure cell with relatively high daytime temperature and large diurnal temperature variation (He et al., 2012b). About 85% of the annual precipitation is received from May to September within the growing season. From 1994 to 2004, mean annual temperature was 0.5 °C and mean annual precipitation was 368 mm (range 290–468 mm) at the weather station Xishui (38°24′N, 100°17′E) at 2800 m a.s.l. (Niu et al., 2006). Mean relative air humidity was 60% and mean annual pan evaporation was 1052 mm in the same period. The dominant soil type of the studied *P. crassifolia* forests are forest gray cinnamon soils (=haplic/calcic Luvisols), mostly with a depth clearly exceeding 1 m. The shallow organic layer mostly consisted of mor-like mold.

2.2. Sample plot selection

Twenty-four 20 m × 20 m plots were selected in a valley (38°33′N, 100°9′E) near Xishui (38°24′N, 100°17′E, 2800 m a.s.l.) in the Qilian Mountain National Nature Reserve. The 24 plots were distributed along six elevational transects with each of the four plots located at different elevations (three plots in the spruce forest belt and one in the shrubland below the lower forest line). Forest

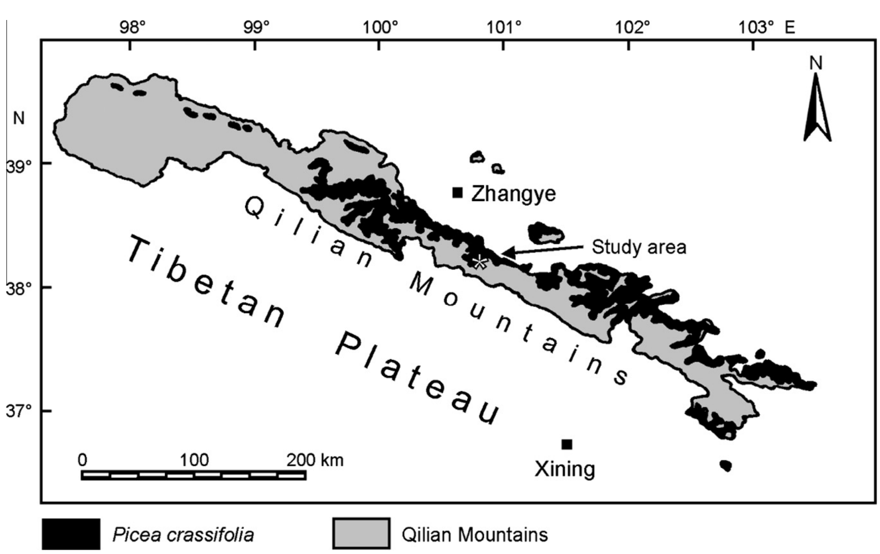

Fig. 1. Qilian Mountains at the north-eastern fringe of the Tibetan Plateau with the position of the study area (asterisk) and the potential distribution of *Picea crassifolia* (after Zhonglin et al., 2009).