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Soil carbon stocks along elevational gradients in Eastern Himalayan mountain forests

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ABSTRACT

We quantified soil organic carbon (SOC) stocks and forest soil characteristics along elevational transects in the temperate conifer forests of Western and Central Bhutan, ranging from 2600 to 4000 m asl. Thereby 82 soil profiles were recorded and classified according to the World Reference Base for Soil Resources from 2014. Based on 19 representative profiles, genetic horizons were sampled and analysed. The results are presented with regard to ecological forest zones. The SOC stocks, up to 100 cm depth, ranged between 56.7 and 337.8 Mg ha^{-1}, with a mean of 168.1 ± 93.0 Mg ha^{-1}. The soils along the elevational gradient showed a unimodal curve for SOC stock with an increase in elevation, a peak at the cool conifer moist forest zone between 3200 and 3400 m asl and a subsequent decrease at the highest elevations. The soil chemical characteristics, CEC and pH-value showed a linear correlation with elevation in the topsoil, with higher values at lower elevations. In deeper soil horizons, elevation had no influence. The nitrogen stocks up to 100 cm depth ranged from 4.2 to 19.1 Mg ha^{-1}, with a mean of 11.4 ± 4.8 Mg ha^{-1}. The elevational distribution of the reference soil groups showed distinct distribution ranges for most of the soils. Cambisols were the most frequently recorded reference soil group at 58%, followed by Podzol, restrained to high elevation, and Stagnosol, at intermediate elevation. Fluvisols occurred only at the lower end of the elevational transects and Phaeozems only at drier site conditions in the cool conifer dry forest zone. The soil characteristics and soil types along the elevational gradient showed a continuous and consistent change, instead of abrupt changes. We interpret these as manifestations of changes of temperature and precipitation with elevation which also drives forest zone distribution. Since forest zone distribution is easily recordable, it can also be used to infer to soil characteristics in these Himalayan forests.

1. Introduction

Soil formation is primarily driven by climate, parent materials and topography, vegetation and disturbances and the time available for soil formation (Jenny, 1941). The influence of climate along elevational and latitudinal gradients (Jenny, 1941) creates differences in both soil and vegetation distinct enough in many regions to be classified into soil and vegetation zones. This has spurred attempts to describe pedogenesis and soil chemical as well as soil physical properties along these gradients since the first half of the last century (e.g. Jenny, 1941; Jenny et al., 1949).

Such elevational gradients lend themselves not only to characterisations of vegetation patterns and nutrient pools in different elevations but also to studies of environmental controls on ecosystem functioning (Asner et al., 2014; Körner, 2007). Elevation can thus serve as a space-for-time substitute of climate change (e.g. Duboc et al., 2014). The recognition of the importance of soils as the largest terrestrial sink for organic carbon (Batjes, 1996) and the fact that reliable data on soil carbon (SOC) stocks is missing for many regions in the world (Pan et al., 2011; Scharlemann et al., 2014) has recently stimulated research on SOC in different regions, vegetation and land use types all over the world including mountain regions (Schawe et al., 2007; Griffiths et al., 2009; Leifeld et al., 2009; Zimmermann et al., 2010; Bu et al., 2012; Dieleman et al., 2013; Prietzel and Christophel, 2014; Dorji et al., 2014a, 2014b; Tashi et al., 2016).

Mountains and soils in mountains are particularly vulnerable to climate - and land-use changes for three reasons: (1) temperature sensitivity of organic matter decomposition decreases exponentially with increasing temperature (Kirschbaum, 1995, 2005), (2) mountain soils also show a high amount of C in labile fractions (Hagedorn et al., 2010)

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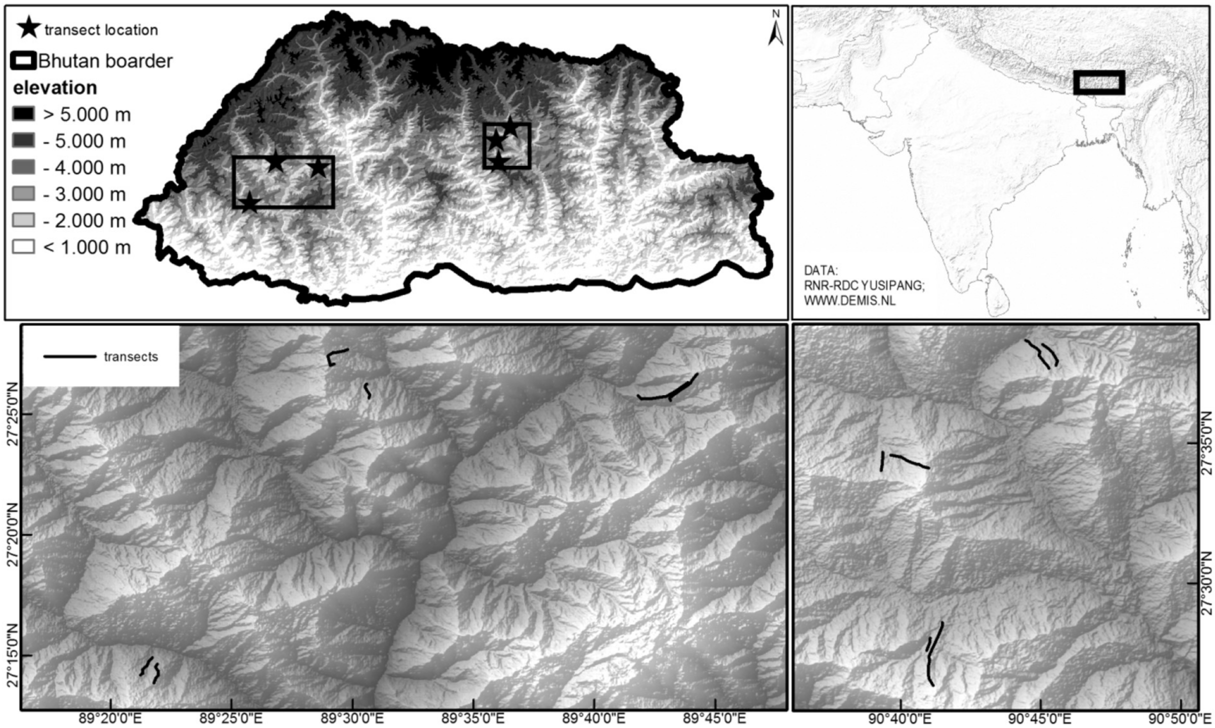

Fig. 1. Location of the study areas and the elevational transects.

and (3) many mountain regions exhibit stronger warming trends by elevation dependent warming (Liu et al., 2009; Oyler et al., 2015; Kotlarski et al., 2015). This corroborates the need for solid data on SOC contents and stocks in ecosystems of higher elevations and latitudes. We therefore aim at providing solid data on soil organic carbon stocks and fundamental information on forest soil characteristics along elevational transects for a study region for which only scarce information is available.

Along elevational gradients, the controls of SOC input of plant matter and decomposition vary with increasing elevation and decreasing temperature. While both production and decomposition rates decrease, the proportional decrease in decomposition is lower, leading to higher SOC contents at higher elevation (Raich et al., 2006; Dai and Huang, 2006; Griffiths et al., 2009; Dieleman et al., 2013; Prietzel and Christophel, 2014; Dorji et al., 2014a; Tashi et al., 2016). Soil moisture is a covarying factor in SOC contents with low and high soil water contents reducing decomposition, thus leading to higher SOC contents (Davidson et al., 2000; Wiesmeier et al., 2012; Prietzel and Christophel, 2014). In areas where SOC did not vary with elevation (Zimmermann et al., 2010) or showed a peaked distribution of SOC (Schawe et al., 2007), large variation within elevational zones masked potential elevational trends, or soil moisture variation in soil types influenced decomposition and production rates differently in different elevations.

The decomposability of plants varies strongly and the quality of litter is a strong control on litter decomposition. Plant species composition was shown to be a stronger driver on litter decomposition than climate (De Long et al., 2016; Cornwell et al., 2008) and can as well cause distinct peaks in SOC contents in vegetation zones with plants of poor litter quality (Djukic et al., 2010; Tashi et al., 2016).

The Himalayas, together with the Hindukush, are the source of freshwater for around 800 million people living downstream (Bolch et al., 2012) and are located in a region forming a tipping element in the Earth's climate system (Lenton et al., 2008). Improving the understanding of environmental controls on carbon stocks and forest soil characteristics in a vulnerable mountain region will contribute to both, adaptation and mitigation strategies to climate change.

The high forest cover in Bhutan (70% (RGoB, 2009)) and the very low anthropogenic impacts in many of these forests predestines the country for studies on drivers of elevational soil and vegetation zonation. This has been corroborated by Wangda and Ohsawa (2006), who found tight linear relations between elevation and forest basal area and maximum tree heights as well as basic soil characteristics.

We therefore hypothesise that (1) SOC contents and stocks increase with increasing altitude; (2) soil chemical characteristics and soil types show a clear elevational zonation and (3) differences in soils drive differences in vegetation types.

2. Methods

2.1. Study area

The study sites are located in the physiographic zone of the inner valleys and passes (Norbu et al., 2003) of west and central Bhutan. This zone with north-south valleys is characterised by a temperate to subalpine climate on slopes, with strong daily freeze-thaw alternation from late autumn to early spring, and drier conditions in the valley floors.

To investigate soil development and characteristics in this extensive zone, two study areas were selected, one in the west located in the administrative area of Thimphu and Paro and one representing the eastern part of the zone located in central Bhutan in the administrative area of Bhumthang (Fig. 1).

The geological bedrock consists of siliceous metasediments varying between mica schists and paragneisses with quartz veins. These belong in the west to the Paro Formation and in the center to the Thimphu Formation (Gansser, 1983; Long et al., 2011). In the study area, the materials for soil development are characterised by softened preweathered bedrock material and aeolian sediments. Recent fluvial sediments were present only at lower slope positions. The influence of aeolian sediments for soil development was described by SSU (2000), Baillie et al. (2004), Caspari (2005) and Caspari et al. (2006, 2009) and could override elevational trends. In neighbouring regions of Eastern Nepal, however, Bäumler and Zech (1994) found that although sediment stratification was present in many of their eleven studied soil profiles, soil development could be inferred from clay content and clay