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Predicting soil respiration for the Qinghai-Tibet Plateau: An empirical comparison of regression models

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ABSTRACT

Alpine ecosystems like the Qinghai-Tibet Plateau strongly respond to global warming. Their soils, containing large carbon stocks, release more carbon dioxide as a possible consequence. Reciprocally, this may intensify climate warming. The Qinghai-Tibet plateau's large and almost inaccessible terrain results in a general data scarcity for this area making the quantification of soil carbon dynamics challenging. The current study provides an area-wide estimation of soil respiration for the Qinghai-Tibet Plateau, which is a key region for climate change studies due to its size and sensitivity. We compared the ability of six regression models to predict soil respiration that were developed within different studies and are based on mean annual air temperature, mean annual precipitation and belowground biomass. We used the WorldClim data sets to approximate annual soil respiration on a regional scale. Compared to field measurements of soil respiration at single spots in different vegetation zones on the Qinghai-Tibet Plateau (max. 1876.63 g C m^{-2} $year^{-1}$), our predicted results (max. 1765.13 g C m^{-2} $year^{-1}$) appear to be consistent. The basic difference between grasslands and forests in soil respiration is indicated by all regression models, however, a more precise differentiation between vegetation types is only exhibited by the regression model based on mean annual precipitation. Overall, this model performs best for most and the largest vegetation zones. Nevertheless, the approximations of the model based on mean annual temperature by Raich and Schlesinger (1992) with a lower constant better represent the vegetation zone of the alpine steppe. With this spatial estimation of soil respiration at a regional scale, a basis for assessing an area-specific potential of greenhouse gas emissions on the Qinghai-Tibet Plateau is provided. Moreover, we quantify a complex soil ecological process for this data-scarce area.

1. Introduction

Soil respiration (SR), defined as the carbon dioxide (CO_2) efflux to the atmosphere, fundamentally impacts the global carbon cycle (Chen et al., 2010). Apart from oceans, soil emits the most carbon dioxide contributing approximately 98 ± 12 Pg C $year^{-1}$ to the global carbon budget (Bond-Lamberty and Thomson, 2010a; Schlesinger and Andrews, 2000; Valentini et al., 2000). With more than 1500 Pg C, soils hold the largest amount of carbon in terrestrial ecosystems (Amundson, 2001; Raich and Schlesinger, 1992) roughly double that of the atmospheric CO_2–C pool (Jia et al., 2006). On a global scale, ~10% of the atmospheric CO_2 passes through soil annually (Bond-Lamberty and Thomson, 2010b). Therefore, a small increase in the amount of soil CO_2 efflux, especially across wide-spread areas, can considerably influence atmospheric CO_2 concentrations, potentially increasing global warming (Rodeghiero and Cescatti, 2005; Rodeghiero et al., 2013; Davidson and Janssens, 2006; Schlesinger and Andrews, 2000).

The ecologically fragile Qinghai-Tibet Plateau is a key region for examining ecosystem processes due to its sensitivity and comparatively low human impact (Fan et al., 2010; Yang et al., 2009; Liu and Chen, 2000). Moreover, the plateau is of high significance for studies on soil respiration (SR) (Geng et al., 2012) because of its important role in the global carbon cycle and remarkable contribution to the global carbon budget. As the highest and spatially most extended plateau on earth, the Qinghai-Tibet Plateau influences both regional and global climates

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Abbreviations: SR, soil respiration; C, carbon; CO_2, carbon dioxide; MAT, mean annual temperature; MAP, mean annual precipitation; BGB, belowground biomass.

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significantly (Zhong et al., 2010; Wang et al., 2006). It has also been called the ‘driving force’ or ‘amplifier’ of global warming (Kang et al., 2010) due to its large size and high altitude but also because of its effects by means of thermal and mechanical forces (Kutzbach et al., 2008; Duan and Wu, 2005; Manabe and Terpstra, 1974). However, climate change likewise influences the Qinghai-Tibet Plateau (Zhang et al., 2010). It is one of the regions of highest sensitivity to global warming mainly due to its extreme elevation (Zhong et al., 2010; Zhang et al., 2007; Luo et al., 2002). The plateau’s temperature is expected to increase far above average in the future (Wang et al., 2008a; Christensen et al., 2007; Liu and Chen, 2000). The cryosphere, commonly considered as the most sensitive indicator to climate change, undergoes rapid changes on the Qinghai-Tibet Plateau (Kang et al., 2010). There, earth’s largest high-altitude and low-latitude permafrost zone, with more than half of its total area influenced by permafrost (Cheng, 2005), shows increasing permafrost degradation (Böhner and Lehmkuhl, 2005; Baumann et al., 2009). This process has been advancing even more than in other high-latitude, low-altitude permafrost regions over the last few decades (Yang et al., 2004). As expected, the further degradation of Tibetan permafrost (Böhner and Lehmkuhl, 2005; Wang et al., 2000) will highly influence its soils mainly by changes in their temperature and moisture patterns (Doerfer et al., 2013; Zhang et al., 2003). Thus, global warming impacts permafrost stability and distribution as well as vegetation and soil characteristics that intensively interact with SR through complex processes (Chapin et al., 2005). Climate warming is even presumed to be the main reason for the increasing global loss of soil carbon to the atmosphere (Jones et al., 2003). This calls attention to the need of a deep understanding of the quantity of SR on the Qinghai-Tibet Plateau (Geng et al., 2012).

Various complex processes characterize SR, representing the activity of soil biota (Reth et al., 2005). Basically, SR is diveded into two components: autotrophic respiration, consisting of root and root-associated (e.g., mycorrhizae) respiration, and heterotrophic respiration, constituted by microbial respiration in the course of soil organic matter decomposition (Joo et al., 2012). Although not entirely congruent (Boone et al., 1998), both of these parts of SR vary with environmental changes (Chen et al., 2010). The variability of SR occurs in temporal and spatial dimensions, both vertically and horizontally (Davidson and Trumbore, 1995). Generally, there is quite a number of biotic and abiotic factors influencing soil CO_2 efflux. Soil respiration is mostly regulated by soil temperature and soil water content (e.g., Raich and Tufekcioglu, 2000; Singh and Gupta, 1977). Water solubilizes organic matter and supports its availability, whereas temperature directly impacts metabolic activities (Koizumi et al., 1999). Soil moisture also controls the response of SR to temperature variation (Wiseman and Seiler, 2004). Other factors affecting soil CO_2 emissions include vegetation (Raich and Tufekcioglu, 2000), soil characteristics, precipitation (Rey et al., 2002), topography (Fang et al., 1998), and land-use regimes (Ewel et al., 1987).

As a multifactorial process with complex interactions and high variability across time and space, SR has always been a challenge to measure and no procedure or model has been commonly accepted as a standard yet (Luo and Zhou, 2006). Widely used methods for field measurements, however, are chamber systems and eddy-covariance systems (Morén and Lindroth, 2000) although they are, in general, highly time and cost intensive (Luo and Zhou, 2006). One possible solution for SR measurement is to apply predictive tools especially for large areas. Due to a lack of data and knowledge of fundamental process components, mechanistic or process-based modelling remains likewise challenging and is still unable to represent SR fully reliable (Luo and Zhou, 2006).

Empirical models have been widely applied for the estimation of likewise complex processes such as soil erosion, which is estimated most commonly with the Universal Soil Loss Equation (Da Silva, 2004). Various regression models for SR have been developed based on field measured SR as a function of different biotic and abiotic variables. These models usually focus on a strongly reduced number of controlling factors of SR (Luo and Zhou, 2006) and thus, potentially overcome the restrictions of limited data, which is especially relevant to large-scale predictions in remote areas. Those empirical models include such climatic variables as mean annual temperature (MAT) and mean annual precipitation (MAP) as input parameters as well as biotic variables such as belowground biomass (BGB). These climatic and biotic variables will be compared in this study.

For the Qinghai-Tibet Plateau, almost two-thirds of which is covered by grassland (Yang et al., 2008; Wang et al., 2006), BGB has been shown to most strongly influence grassland ecosystem SR at a regional scale due to high root biomass density (Geng et al., 2012). In general, temperature and precipitation are widely considered as most effectively representing SR variation in time and space (Bond-Lamberty and Thomson, 2010a; Hashimoto et al., 2015) while MAT and MAP are important candidates as predictors for annual SR. We assume the Qinghai-Tibetan Plateau to represent a global-scale ecosystem given it has both highly heterogenic climate and vegetation. Nevertheless, data for the Qinghai-Tibet Plateau at a sufficient spatial and temporal resolution are generally scarce. Even though the Plateau’s unique role in climate change studies due to its ecological sensibility, the inaccessible and complex terrain complicates research activities resulting in this lack of data. Despite their limitations, empirical models are therefore highly advantageous for predicting SR of the Qinghai-Tibetan Plateau due to its size and specific data acquisition requirements. The need for quantifying highly complex soil ecological processes more accurately for sparsely sampled areas, especially in light of climate change, is captured by such an approach and exemplarily executed for the Qinghai-Tibet Plateau.

Mindful of these challenges, we aim at determining the best regression model for estimating SR on the Qinghai-Tibet Plateau in this study. The ideal algorithm should allow for (1) the calculation of SR on a large scale and (2) for variation with major vegetation types.

2. Material and methods

2.1. Study area

Our study area, the Qinghai-Tibet Plateau, is located in southwestern China. With an area of about $2.6 \times 10^6\,km^2$, it fully covers Tibet and Qinghai provinces, and partially Xinjiang, Gansu, Sichuan, and Yunnan provinces. As the largest plateau on earth, the Qinghai-Tibet Plateau extends from 26°00′12″ N to 39°46′50″ N and from 73°18′52″ E to 104°46′59″ E with a maximum length of approx. 2 945 km from east to west and approx. 1 532 km from south to north. The average altitude of the plateau is 4380 m (Zhang et al., 2002). Surface elevation sharply declines at its border, particularly at the southern end. Overall, eastern and western regions differ markedly with regard to geomorphology, vegetation and climatic characteristics (Smith and Shi, 1995). The unique geographical position of the Qinghai-Tibet Plateau results in an azonal, plateau monsoon climate from a subtropical to a temperate mountain climate (Zhuang et al., 2010; Zhong et al., 2010) with strong solar radiation, low air temperature, large daily temperature variations yet low differences between annual mean temperatures (Zhong et al., 2010). The mean temperature in July, the warmest month, varies from 7 °C to 15 °C and from −1 °C to −7 °C in January, the coldest month. Average annual temperature is 1.6 °C (Yang et al., 2009). Precipitation amounts to about 413.6 mm per year (Yang et al., 2009), with more than 60–90% falling in the wet and