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

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A B S T R A C T

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.

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1. Introduction

Soil respiration (SR), defined as the carbon dioxide (CO₂) 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 CO₂–C pool (Jia et al., 2006). On a global scale, ~10% of the atmospheric CO₂ passes through soil annually (Bond-Lamberty and Thomson, 2010b). Therefore, a small increase in the amount of soil CO₂ efflux, especially across wide-spread areas, can considerably influence atmospheric CO₂ 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...
significant (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 Lehnhkuhl, 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 Lehnhkuhl, 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 divided 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 CO₂ 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 (Wise-man and Seiler, 2004). Other factors affecting soil CO₂ 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 × 10⁶ km², 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
humid summers (June–September) and 10% at maximum in the cool, arid winters (November–February) (Xu et al., 2008). Summer precipitation can be less than 50 mm in the northwest (Xu et al., 2008). Generally, a decrease both in temperature and in precipitation from the south-eastern to the north-western part of the plateau is apparent (Immerzeel et al., 2005). The topographic setting as well as atmospheric conditions determine the sequence of alpine forests, meadows, steppes and deserts from southeast to northwest (Fig. 1), which follows a climatic gradient from warm and humid to cold and arid according to the influence of the South Asian monsoon (Pei et al., 2009; Zheng, 1996). Alpine steppes and meadows dominate the undisturbed vegetation with Stipa species and Kobresia meadows as major vegetation types. Alpine grasslands cover more than 60% of the study area (Yang et al., 2008; Wang et al., 2006). Long freezing periods and thus, relatively short growing seasons characterize the plateau’s climate (Yu et al., 2010). Its vegetation is regarded as comparatively natural (Schroeder and Winjum, 1995), although parts of the plateau in the humid Southeast have undergone human-induced changes with Kobresia pygmaea growing instead of forests and grasslands (Miehe et al., 2014). Continuous, complex pedogenetic processes on the Qinghai-Tibet Plateau typically result in young and highly diverse soils with distinct degradation characteristics, exhibiting a strong influence by permafrost regimes (Baumann et al., 2014).

2.2. Geodatabase and processing

In this case study, three data sets were used to estimate SR from temperature, precipitation and belowground biomass data. All data sets were projected into the Universal Transverse Mercator coordinate system WGS 1984, Zone 45 N. The data sets for MAT and MAP were obtained from the WorldClim data set available at http://worldclim.com. This latter database was compiled from a considerable number of various sources, such as the Global Historical Climate Network, World Meteorological Organization and the Food and Agricultural Organization, with a resolution of 1 × 1 km and representing the current climate conditions from ca. 1950 to 2000. Data from climate stations were interpolated with latitude, longitude and altitude as independent variables (for more detailed information see Hijmans et al., 2005). BGB data with a spatial resolution of 1 × 1 km have been generated by the application of an exponential regression model developed by Luo et al. (2005). When modeling, they incorporated various climate and vegetation data of the Qinghai-Tibet Plateau and presented the different resulting models based on various input parameters. When these models were compared, the model with MAT as an input parameter excels when applied to the Qinghai-Tibet Plateau (Bosch et al., unpublished results). We therefore use the data set generated with this MAT-dependent model in the present study. The input MAT data set of this calculated BGB data set also originate from WorldClim data (Bosch et al., unpublished results).

2.3. Soil respiration calculation and evaluation

SR was calculated based on MAT, MAP and BGB using six different regression models (Table 1).

Due to a scarce spatial data resolution for deriving the amount of SR on the Qinghai-Tibet Plateau, we made use of field observations of SR from other studies (Table 2). To evaluate the
power of the regression models applied in this study, we compared our results with those reported by Cao et al. (2004), Zhang et al. (2005, 2009), Li and Sun (2011), Geng et al. (2012), Chen et al. (2014) and Wang et al. (2014). The observation sites were located in three different vegetation types: alpine steppe, alpine meadows and forest. These vegetation types were identified in each of the studies we used for comparison. Thus, the evaluation sites comprise the widest-spread vegetation types and the majority of vegetation cover on the plateau (Fig. 1). The sites also cover various climatic conditions and altitudes (3000–5105 m a.s.l.).

### Table 1
Regression models to approximate soil respiration.

<table>
<thead>
<tr>
<th>Type of regression</th>
<th>Region, vegetation type</th>
<th>Equation</th>
<th>Parameters</th>
<th>Author(s)</th>
<th>( r^2 )</th>
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<tbody>
<tr>
<td>Regression based on mean annual temperature ( T )</td>
<td>Global</td>
<td>( SR = 25.67 + 300 )</td>
<td>( SR = \text{annual soil respiration rate (g C m}^{-2} \text{ year}^{-1}), T = \text{mean annual temperature (°C)} )</td>
<td>Raich and Schlesinger (1992) (MAT I), Chinner (2004) (MAT II)</td>
<td>0.42</td>
</tr>
<tr>
<td>Regression based on mean annual precipitation ( P )</td>
<td>Micronesia and Hawaii, peatlands</td>
<td>( Y = 265.9 + (27.7 \times MAT) )</td>
<td>( Y = \text{annual soil respiration rate (g C m}^{-2} \text{ year}^{-1}), MAT = \text{mean annual temperature (°C)} )</td>
<td>Raich and Schlesinger (1992)</td>
<td>0.46</td>
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<tr>
<td>Regression based on mean annual temperature ( T ), mean annual precipitation ( P )</td>
<td>Global</td>
<td>( SR = 0.391P + 155 )</td>
<td>( SR = \text{annual soil respiration rate (g C m}^{-2} \text{ year}^{-1}), P = \text{mean annual precipitation (mm)} )</td>
<td>Raich and Schlesinger (1992) (MAT I), Raich and Schlesinger (1992) (MAT II)</td>
<td>0.34</td>
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<tr>
<td>Regression based on mean annual precipitation ( P ), ( T )</td>
<td>Global</td>
<td>( SR = (9.267T) + (0.0127TP) + 289 )</td>
<td>( SR = \text{annual soil respiration rate (g C m}^{-2} \text{ year}^{-1}), P = \text{mean annual precipitation (mm)}, T = \text{mean annual temperature (°C)} )</td>
<td>Raich and Schlesinger (1992) (MAT I), Raich and Schlesinger (1992) (MAT II)</td>
<td>0.50</td>
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<tr>
<td>Regression based on root biomass</td>
<td>India, tropical forest soil</td>
<td>( y = 0.32x + 176.6 )</td>
<td>( y = \text{soil respiration (mg CO}_2 \text{ m}^{-2} \text{ h}^{-1}), x = \text{total root biomass (g m}^{-2} )</td>
<td>Behera et al. (1996)</td>
<td>0.89</td>
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### Table 2
Range of soil respiration for different vegetation types on the Qinghai-Tibet Plateau measured by Cao et al. (2004), Zhang et al. (2005), Li et al. (2011), Zhang et al. (2009), Geng et al. (2012), Chen et al. (2014), Wang et al. (2014) and calculated based on regression models.

<table>
<thead>
<tr>
<th>Vegetation type</th>
<th>Cao et al. (2004) (n = 1)</th>
<th>Zhang et al. (2005) (n = 1)</th>
<th>Li and Sun (2011) (n = 1)</th>
<th>Zhang et al. (2009) (n = 60)</th>
<th>Geng et al. (2012) (n = 18; ( n_{\text{AL}} = 29 ))</th>
<th>Chen et al. (2014) (n = 2)</th>
<th>Wang et al. (2014) (n = 1)</th>
<th>All field samples (n = 104)</th>
<th>Regression model based on MAT I</th>
<th>MAT II</th>
<th>MAP</th>
<th>MAT and MAP I</th>
<th>MAT and MAP II</th>
<th>BGB</th>
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<tr>
<td>Alpine steppe (AS)</td>
<td>143.53</td>
<td>50.47</td>
<td>522.87</td>
<td>150.04</td>
<td>103.64</td>
<td>212.65</td>
<td>214.76</td>
<td>201.74</td>
<td>422.52</td>
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<tr>
<td>Alpine meadow (AM)</td>
<td>555.37</td>
<td>529.54</td>
<td>561.55</td>
<td>333.22</td>
<td>285.82</td>
<td>295.7</td>
<td>290.37</td>
<td>441.3</td>
<td>422.6</td>
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<tr>
<td>Forest (F)</td>
<td>714.17</td>
<td>633.76</td>
<td>647.88</td>
<td>592.54</td>
<td>430.05</td>
<td>436.8</td>
<td>422.78</td>
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<tr>
<td>All</td>
<td>696</td>
<td>590.84</td>
<td>474.34</td>
<td>532.1</td>
<td>434.9</td>
<td>439.05</td>
<td>422.78</td>
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All samples except the ones from the studies of Chen et al. (2014) and Wang et al. (2014) were collected in the peak season of soil respiration from June to August. Daily means were calculated based on several measurements per day in each study. To compare annual data calculated by the regression models, we summed up daily means to give annual SR values. However, this leads to a systematic overestimation of annual SR, because the daily means were estimated based on measurements during peak season months. We therefore developed and implemented a seasonality correction factor to account for this. This seasonality correction factor is based on calculations by Cao et al. (2004). The annual total sum of daily average SR values is about 1.99 times higher than the estimation of annual SR values where seasonal variation of SR is considered. We accordingly corrected all cumulative SR annual values by a factor of 0.33 except for the evaluation data from Chen et al. (2014) and Wang et al. (2014). The data of Chen et al. (2014) are based on measurements every 10 days throughout an entire year after having conducted extra measurements to find the optimal measurement time representing daily means. Wang et al. (2014) summed daily means based on hourly measurements throughout four years to calculate annual estimates, which we averaged to one mean annual value.

Ranges of the model-based SR values of each vegetation zone are based on grid points according to the geographical coordinates from the field sampling sites of the literature data. Since information on precise georeferences was not given in Chen et al. (2014), personal communication with Luo (2015) served as an additional source of information. The range of all field measurements throughout the different vegetation zones is compared to all calculated values of the whole plateau for each model. Moreover, we compared the mean of all field data to the mean of all calculated SR values for the whole plateau for each model.

3. Results and discussion

The resulting SR estimates of the applied regression models ranged from a low of −300.08 to a maximum of 1762.17 g C m⁻² year⁻¹. All estimates generally fit the order of magnitude of the data measured in the field (Table 2). Negative pixel values arose from the regression models involving MAT as input parameter, representing areas where the model MAT is −9.59 °C and below as for the case of Chimner (2004). The linear regression models did not adequately describe the shape of the true temperature-SR relation for very low temperatures. We, therefore, showed negative results as zero by assuming that negligible metabolic activity occurs below a certain threshold. In Chimner’s (2004) model this threshold was −9.59 °C. An approximate limit of respiratory processes related to a minimum temperature was thereby reflected. The variation of SR with vegetation types was resembled by all regression models, however, to a different extent (Table 2, Fig. 2).

3.1. SR of grasslands

The ranges of all regression models were within the range of the directly measured SR samples (50.47–522.87 g C m⁻² year⁻¹) for the vegetation zone of alpine steppe. The range of the calculations of the model based on MAT by Raich and Schlesinger (1992) (MAT II) (103.64–331.44 g C m⁻² year⁻¹) most closely matched the range of the field measured samples followed by the MAT I-based model and MAP-based model (150.04–360.57 g C m⁻² year⁻¹ and 221.65–339.65 g C m⁻² year⁻¹, respectively). Also, the relative error was lowest for the MAT II-based model (Table 2, Fig. 3). Ranges, absolute minimum and maximum SRs estimated by the regression models that combine MAT and MAP as input parameters (with the higher constant: MATP I; with the lower constant: MATP II) were very similar (MATP I: 214.76–318.44 g C m⁻² year⁻¹; MATP II: 201.74–310.82 g C m⁻² year⁻¹) but were less congruent with the
directly measured values than particularly the MAT-based regression models. The result of the MAT II-based model with regard to its absolute minimum value estimation was closest to the field measured data, although it was the maximum SR of the BGB-based model (422.64 g C m\(^{-2}\) year\(^{-1}\)) that corresponded best to the absolute maximum of the field data. However, the range of SR values predicted by the BGB-based model was a large number of times smaller than the range of the directly measured values. Moreover, the relative error of BGB-based model SR estimates was the highest. Thus, the MAT II-based regression model most closely represented the field measurements for the vegetation of alpine steppe.

The alpine meadows field values generally exhibited a wider range and higher minimum and maximum values (144.95–1876.63 g C m\(^{-2}\) year\(^{-1}\)) than the field data for the alpine steppe. Generally, this comparatively wide range resulted from large differences in SR even between plant communities causing extremely high small-scale variability (Zhang et al., 2009) that cannot be reflected in the 1 × 1 km resolution at hand. Excluding samples that purely consisted of *K. tibetica* with SR values of 565.58–1876.63 g C m\(^{-2}\) year\(^{-1}\) (Zhang et al., 2009; \(n = 20\)) and from 594.05 to 1666.97 g C m\(^{-2}\) year\(^{-1}\) for the three samples of Geng et al. (2012), the maximum value would have been distinctly lower (1410.71 g C m\(^{-2}\) year\(^{-1}\)). With 7 exceptions out of a total of 76 samples, all SR samples would be below 1000 g C m\(^{-2}\) year\(^{-1},\) which clearly shows that the range of the vast majority was lower and about one third to one half smaller (144.95 to below 1000 g C m\(^{-2}\) year\(^{-1}\)). Predominantly occurring at wet sites, the plant physiological characteristics of *K. tibetica* communities enable them to develop an extensive root system in this environment resulting in a much higher BGB (Wang et al., 2008b) and consequently in strongly increased SR (Geng et al., 2012; Zhang et al., 2009). None of the regression models predicted such extraordinarily high values for these special plant communities. The spatial variability within the small distances between single plant communities that differed highly in their SR cannot be represented by a 1 × 1 km resolution as well. Of all regression models, however, the MAP-based one best concurred with the direct measurements except for the minimum. The minimum values of the models including MAT as the input parameter align more closely with smaller relative errors of only up to 0.01% in the minima for the MAT I-based model. It was nevertheless the MAP-based regression model which proved to be the most appropriate for the alpine meadows as its mean relative error was lowest (55.37%) except from the model based on BGB (46.88%). The latter, however, is not adequate due its extremely small range (422.52–422.66 g C m\(^{-2}\) year\(^{-1}\)). The recognition that the MAP-based model as most appropriate one was further confirmed by the fact that this model was the only one to clearly distinguish between alpine steppe and alpine meadows.

### 3.2. SR of forests

Compared to the average field measurement value of grasslands excluding *K. tibetica* samples (622.05 g C m\(^{-2}\) year\(^{-1}\)) and compared to the model-based values for grasslands, higher SR values generally occurred in forests which was also reflected by the calculations of all models. The models that included MAT as an input parameter performed very similarly; however, their estimates (430.05–474.34 g C m\(^{-2}\) year\(^{-1}\)) are not as close to the field measured values (643.76–908.84 g C m\(^{-2}\) year\(^{-1}\)) as the approximations calculated by the MAP-based regression model (529.54–532.1 g C m\(^{-2}\) year\(^{-1}\)). Throughout all vegetation zones, the BGB-based results exhibited a small range within the range of MAT-based estimates. The MAP-based model had one of the lowest one (31.62%) relative mean errors compared to all other models (37.56–45.53%). The regression model based on MAP showed the closest approximations to field measurements and thus, performed best for the forest vegetation zone.

For the Qinghai-Tibetan Plateau as a whole, the regression models involving MAP as the input parameter were closest to all field measurement data of grassland types and forests with respect to the mean SR, the relative error of the mean, the minimum, the maximum and range. However, two exceptions were noted for the BGB-based model. These were the mean and the mean relative error for all data that arose from the comparatively static character of the values from the BGB-based model throughout the vegetation zones. This model was generally most inadequate with the highest mean relative error. It also underperformed with a particularly small range representing less than 1% of the field data range which appeared to be characteristic for this model throughout all vegetation zones. The model solely based on MAP, was the best model also in comparison to the regression models that included MAP as an input parameter. This was true especially for the mean...
value and its relative error (299.18 g C m\(^{-2}\) year\(^{-1}\); 58.61%), indicating the peculiar importance of precipitation for SR in rather arid regions (Curiel Yuste et al., 2003).

Overall, the estimates of all regression models were within the order of magnitude of the values based on field measurements. All model-based estimates indicated the basic difference in SR between grasslands and forests. For the alpine steppe vegetation zone, the MAT II-based regression model was preferable as it most closely approximated direct field measurements. On the other hand, the regression model with MAP as an input parameter decidedly performed best for alpine meadows, forests and the range of the whole plateau. Generally, although developed for very different regions, both MAT-based models behave similarly across all vegetation types.

However, important uncertainties of the predicted values are associated with the regression models. Indicated by their coefficient of determination \((r^2 = 0.34–0.88)\), the models cannot fully explain the data variability. This reflects highly complex interdependencies between SR and all its controlling factors. Moreover, discrepancies would be expected since none of the regression models have been developed for the Qinghai-Tibet Plateau or for this certain kind of application.

Further deficiencies in the calculations of all regression models may arise from the development of the WorldClim data sets that show lower precision for poorly sampled regions like the Qinghai-Tibet Plateau (Maussion et al., 2011; Böhner, 2006; Hijmans et al., 2005). The same holds true for areas on the plateau with complex topography where a 1 × 1 km resolution does not capture all potential variation (Hijmans et al., 2005). Additionally, the input data set with BGB data exhibits limitations especially for forests and extraordinary high values (Bosch et al., unpublished results).

Furthermore, high small-scale variability of SR especially in alpine meadows is not captured by a data resolution of 1 × 1 km. The comparatively high values in alpine meadows, particularly of *K. tibetica* plant communities, were not predicted by any regression model. This strong difference in SR rates between these communities and other alpine meadow plant communities results in large differences of SR over short distances, which can only be represented with higher spatial resolution. Moreover, vegetation degradation and grazing effects comprising about 35% of the Qinghai-Tibet Plateau and their decreasing influence on SR (Wen et al., 2013; Cao et al., 2004) were not integrated in our estimations and constraints these predictions of SR.

The evaluation data used in this study account for another weakness. Although all studies use chamber-based methods for their measurements, there are differences between the various chamber methods that may cause further inaccuracies of the values. In addition, daily means were calculated based on a different number of daily measurements and measurement times. Although for some of the studies, extra measurements were taken to determine the optimal number and time of measurement for the daily mean, discrepancies among the results remain. Also, the annual SR values for forests have been estimated based on continuous measurements throughout one whole year in contrast to the values of all other studies where seasonality was not considered a major factor.

The estimation of annual values based on daily means of field measurements poses other constraints. The higher the temporal resolution of data, the higher the variability of the cumulative values. This tendency increases with larger differences in the target temporal resolution, which eventually ranges from seconds to a year. This may result in ranges of values that are too large. The seasonality correction factor derived from the estimations by Cao et al. (2004) for alpine meadows might vary for other vegetation types such as forests as the cumulative SR in the peak month accounts for only about 20% of the total annual SR (Chen et al., 2014). The larger difference in SR between forests and grasslands compared to the difference between alpine steppes and alpine meadows can be explained as forests can often adjust better to environmental (e.g., temperature) variation. Furthermore, the

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**Fig. 4.** Spatial distribution of soil respiration on the Qinghai-Tibet Plateau based on mean annual precipitation according to Raich and Schlesinger (1992). Soil respiration is in SI unit (Mg ha\(^{-1}\)). The spatial resolution of the grids is 1 × 1 km.
values provided by Cao et al. (2004) are themselves estimations based on (1) data obtained from chamber method measurements, which have inherent limitations, and on (2) equations based on soil temperature with an $r^2 = 0.82$. It should be noted that approximations for SR obtained from annual values in general are inevitably not as accurate as calculations from periodic or continuous data. However, a recent study (Wang et al., 2014) provides hourly data throughout four years. We developed a seasonality correction factor of 0.55 based on their results, which corresponded to the one we used based on Cao et al. (2004) results. The relative error of the annual total of SR based on cumulative daily means is hence lower than for Cao et al. (2004). In Wang et al. (2014) study, however, the daily mean refers to the whole growing season in contrast to the daily means of all other evaluation data studies including Cao et al. (2004), which refer to the peak months in the growing season. Therefore, the seasonality correction factor based on the results of Cao et al. (2004) still achieved more accurate results.

In conclusion, we recommend the MAP-based regression model for area-wide, pixel-based calculations of SR on the Qinghai-Tibet Plateau (Fig. 4) given our analysis of the results in view of the dependence of SR on vegetation. Considering the fact that this regression model only performs worse than the models including MAT as an input parameter for the minimum value in the alpine steppe and, first and foremost, clearly excels for alpine meadows and forests, it is to be given preference over all regression models. More importantly, the MAP-based regression model is the only one that shows a clear difference between the vegetation types alpine steppe and alpine meadows. We, therefore, consider it as the superior model for a pixel-based calculation of SR on the Qinghai-Tibet Plateau. Our study provides an area-wide quantification of a multifactorial soil ecological process assessed by a comparison of different regression models against the background of strong data limitations.

4. Conclusion

Estimates of SR are crucial in understanding soil carbon dynamics of terrestrial ecosystems. Since SR data collection requires significant time and cost, data at a sufficient spatial resolution for large areas, especially for the Qinghai-Tibet Plateau, are generally scarce.

To overcome this restriction of limited data, we tested regression models which can be run with climate and BGB data, which is advantageous for an area-wide calculation of scenarios.

Results of various studies indicate the important role of temperature, precipitation and BGB with regard to SR. We conclude from our study that the regression model based on MAP performs best in calculating SR for the Qinghai-Tibet Plateau according to the comparison with our evaluation data sets and other regression models. The MAP-based model can be run with limited data and best represents the most important and spread-out vegetation zones on the Qinghai-Tibet Plateau. The incorporation of other regression models would, however, improve the accuracy of SR approximations for special vegetation types. Our approach of estimating SR with scarce data is well within the same range of directly measured field data from other studies on the Qinghai-Tibet Plateau. The spatially distinct SR calculation at a comparatively high spatial resolution allows for assessing potential area-specific greenhouse gas emission on the Qinghai-Tibet Plateau.

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Appendix A. Supplementary data

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References
