Pedobiologia xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Pedobiologia - Journal of Soil Ecology

journal homepage: www.elsevier.de/pedobi

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

Anna Bosch[a,*], Corina Dörfer[a], Jin-Sheng He[b,c], Karsten Schmidt[a], Thomas Scholten[a]

[a] University of Tuebingen, Department of Geosciences, Chair of Soil Science and Geomorphology, Tübingen, Germany
[b] Key Laboratory of Adaptation and Evolution of Plateau Biota, Northwest Institute of Plateau Biology, Chinese Academy of Sciences, Xining 810008, China
[c] Department of Ecology, College of Urban and Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, China

ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form 27 January 2016
Accepted 28 January 2016

Keywords:
Soil respiration
Regression model
Qinghai-Tibet Plateau
WorldClim

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.

© 2016 Elsevier GmbH. All rights reserved.

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 $98 \pm 12\,Pg\,C\,year^{-1}$ 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

---

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

[*] Corresponding author at: University of Tuebingen, Department of Geosciences, Chair of Soil Science and Geomorphology, Ruemelinstraße 19-23, D-72070 Tübingen, Germany. Fax: +49 7071 29 5391.

E-mail address: anna.bosch@geographie.uni-tuebingen.de (A. Bosch).

http://dx.doi.org/10.1016/j.pedobi.2016.01.002
0031-4056/© 2016 Elsevier GmbH. All rights reserved.

Please cite this article in press as: Bosch, A., et al., Predicting soil respiration for the Qinghai-Tibet Plateau: An empirical comparison of regression models. Pedobiologia - J. Soil Ecol. (2016), http://dx.doi.org/10.1016/j.pedobi.2016.01.002

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 2.6×10^6 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

Please cite this article in press as: Bosch, A., et al., Predicting soil respiration for the Qinghai-Tibet Plateau: An empirical comparison of regression models. Pedobiologia - J. Soil Ecol. (2016), http://dx.doi.org/10.1016/j.pedobi.2016.01.002

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

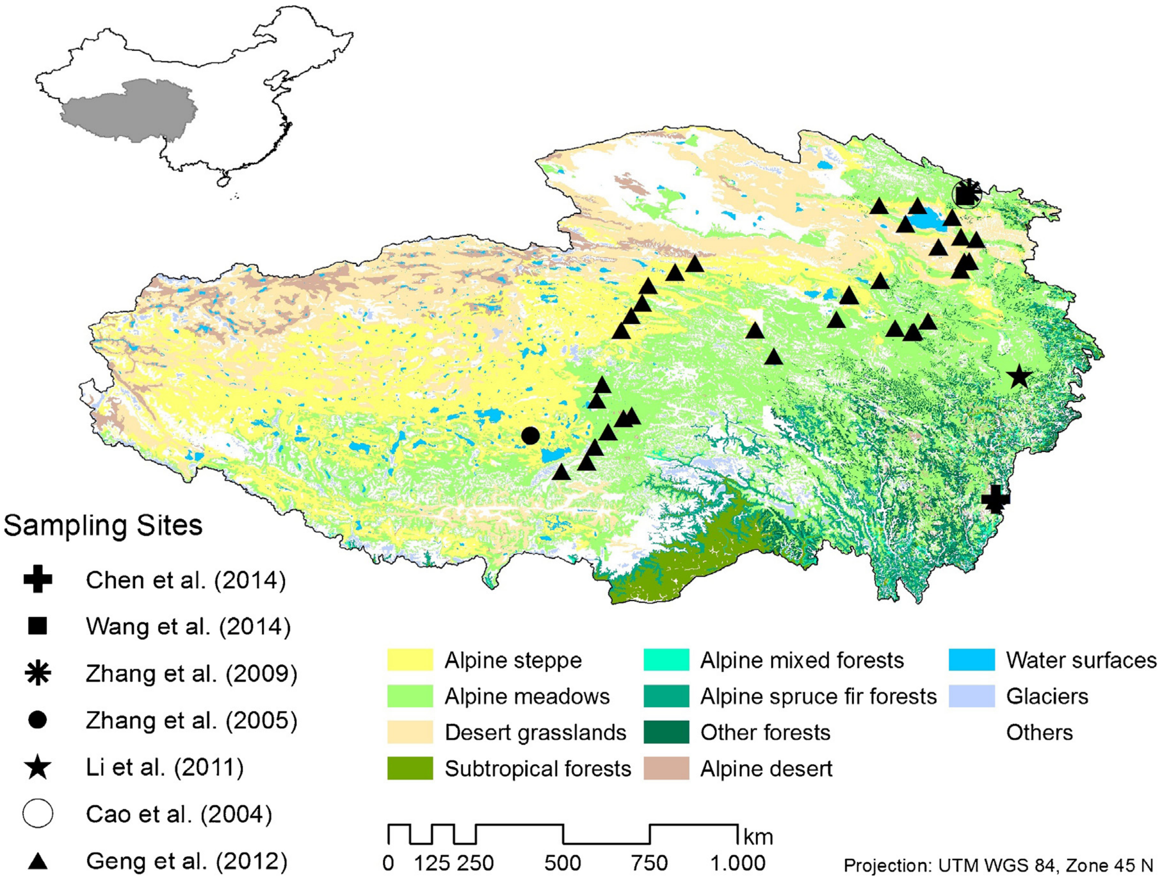

Fig. 1. Vegetation map of the Qinghai-Tibet Plateau based on data sets for land cover in Tibet with sampling localities of Cao et al. (2004), Zhang et al. (2005), Li and Sun (2011), Zhang et al. (2009), Geng et al. (2012) and Wang et al. (2014), (Tibetan and Himalayan Library, 2002).

Please cite this article in press as: Bosch, A., et al., Predicting soil respiration for the Qinghai-Tibet Plateau: An empirical comparison of regression models. Pedobiologia - J. Soil Ecol. (2016), http://dx.doi.org/10.1016/j.pedobi.2016.01.002

Table 1
Regression models to approximate soil respiration.

Type of regression	Region, vegetation type	Equation	Parameters	Author(s)	r^2
Regression based on mean annual temperature T	Global	$SR = 25.6T + 300$	SR = annual soil respiration rate (g C m^{-2} year^{-1}), T = mean annual temperature (°C),	Raich and Schlesinger (1992) (MAT I)	0.42
	Micronesia and Hawaii, peatlands	$Y = 265.9 + (27.7 \times \text{MAT})$	Y = annual soil respiration rate (g C m^{-2} year^{-1}), MAT = mean annual temperature (°C)	Chimner (2004) (MAT II)	0.46
Regression based on mean annual precipitation P	Global	$SR = 0.391P + 155$	SR = annual soil respiration rate (g C m^{-2} year^{-1}), P = mean annual precipitation (mm)	Raich and Schlesinger (1992)	0.34
Regression based on mean annual temperature T, mean annual precipitation P	Global	$SR = (9.26T) + (0.0127TP) + 289$	SR = annual soil respiration rate (g C m^{-2} year^{-1}), T = mean annual temperature (°C), P = mean annual precipitation (mm)	Raich and Schlesinger (1992) (MATP I)	0.50
	Global	$SR = (9.88T) + (0.0344P) + (0.0112TP) + 268$	SR = annual soil respiration rate (g C m^{-2} year^{-1}), T = mean annual temperature (°C), P = mean annual precipitation (mm)	Raich and Schlesinger (1992) (MATP II)	0.50
Regression based on root biomass	India, tropical forest soil	$y = 0.32x + 176.6$	y = soil respiration (mg CO_2 m^{-2} h^{-1}), x = total root biomass (g m^{-2})	Behera et al. (1990)	0.89

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 are 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.). The

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.

Vegetation type		Cao et al. (2004) (n = 1)	Zhang et al. (2005) (n = 1)	Li and Sun (2011) (n = 1)	Zhang et al. (2009) (n = 60)	Geng et al. (2012) (n_{AS} = 18; n_{AM} = 20)	Chen et al. (2014) (n = 2)	Wang et al. (2014) (n = 1)	All field samples (n = 104)	Regression model based on					
										MAT I	MAT II	MAP	MAT and MAP I	MAT and MAP II	BGB
		(g C m^{-2} year^{-1})													
Alpine steppe (AS)	Range	–	143.53	–	–	50.47–522.87	–	–	50.47–522.87	150.04–360.57	103.64–331.44	221.65–339.65	214.76–318.44	201.74–310.82	422.52–422.64
	Mean	–	–	–	–	–	–	–	254.6	262.86	225.71	283.17	270.64	260.60	422.57
	Median	–	–	–	–	–	–	–	245.9	274.39	238.19	279.87	274.54	263.33	422.57
	(Mean rel. error [%])	–	–	–	–	–	–	–	–	*(48.70)*	*(41.32)*	*(63.14)*	*(57.22)*	*(56.03)*	*(135.34)*
Alpine meadow (AM)	Range	555.37	–	714.17	326.15–1876.63	144.95–1666.97	–	696	144.95–1876.63	146.39–376.79	99.69–349.00	266.95–561.55	205.75–345.41	197.37–357.82	422.52–422.66
	Mean	–	–	–	–	–	–	–	828.77	293.36	258.87	333.22	285.82	280.66	422.59
	Median	–	–	–	–	–	–	–	795.95	311.39	278.23	333.48	295.7	290.37	422.6
	(Mean rel. error [%])	–	–	–	–	–	–	–	–	*(60.87)*	*(64.59)*	*(55.37)*	*(61.26)*	*(60.31)*	*(46.88)*
Forest (F)	Range	–	–	–	–	–	643.76–908.84	–	643.76–908.84	467.88–474.34	447.55–454.54	529.54–532.1	430.05–434.91	436.8–441.3	422.78–422.79
	Mean	–	–	–	–	–	–	–	776.3	471.11	451.04	530.82	432.48	439.05	422.78
	Median	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	(Mean rel. error [%])	–	–	–	–	–	–	–	–	*(37.56)*	*(41.89)*	*(31.62)*	*(44.28)*	*(43.44)*	*(45.53)*
All	Range	–	–	–	–	–	–	–	50.47–1876.63	−223.07–914.4	−300.08–930.7	161.64–1762.17	15.83–1641.16	7.98–1639.56	422.48–423.76
	Mean	–	–	–	–	–	–	–	722.86	257.13	219.52	299.18	281.14	270.89	422.60
	Median	–	–	–	–	–	–	–	713.00	237.06	197.80	251.57	214.61	200.61	422.52
	(Mean rel. error [%])	–	–	–	–	–	–	–	–	*(64.42)*	*(69.63)*	*(58.61)*	*(61.10)*	*(62.52)*	*(41.53)*

Please cite this article in press as: Bosch, A., et al., Predicting soil respiration for the Qinghai-Tibet Plateau: An empirical comparison of regression models. Pedobiologia - J. Soil Ecol. (2016), http://dx.doi.org/10.1016/j.pedobi.2016.01.002

sampling sites of Chen et al. (2014) located in the eastern part of the plateau are not displayed in Fig. 1.

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 exept 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

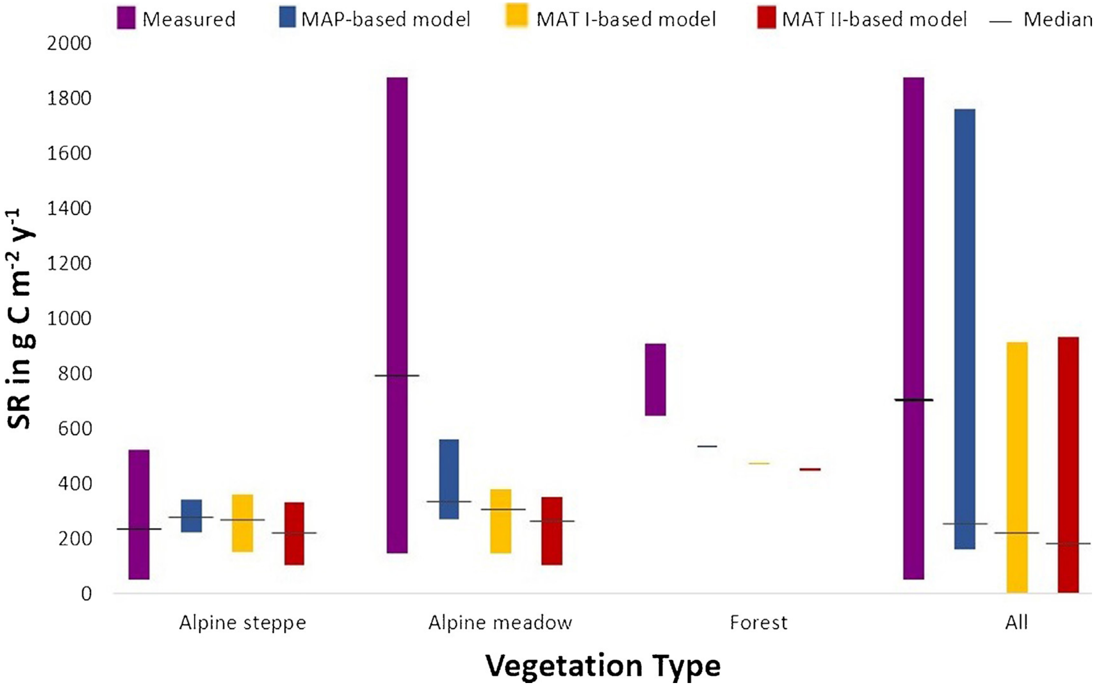

Fig. 2. Range of soil respiration for different vegetation types on the Qinghai-Tibet Plateau measured by Cao et al. (2004), Zhang et al. (2005), Li and Sun (2011), Zhang et al. (2009), Geng et al. (2012), Chen et al. (2014) and calculated based on the mean annual precipitation-based, mean annual temperature I-based and mean annual temperature II-based regression models.

Please cite this article in press as: Bosch, A., et al., Predicting soil respiration for the Qinghai-Tibet Plateau: An empirical comparison of regression models. Pedobiologia - J. Soil Ecol. (2016), http://dx.doi.org/10.1016/j.pedobi.2016.01.002

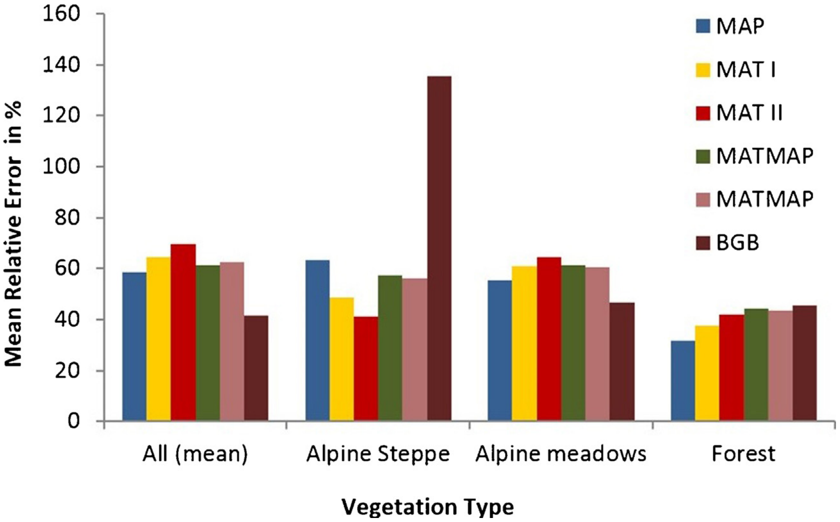

Fig. 3. Mean relative error of regression model estimates for the sampling sites of the respecitve vegetation zones.

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., 2008 b) 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 prooved 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

Please cite this article in press as: Bosch, A., et al., Predicting soil respiration for the Qinghai-Tibet Plateau: An empirical comparison of regression models. Pedobiologia - J. Soil Ecol. (2016), http://dx.doi.org/10.1016/j.pedobi.2016.01.002

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

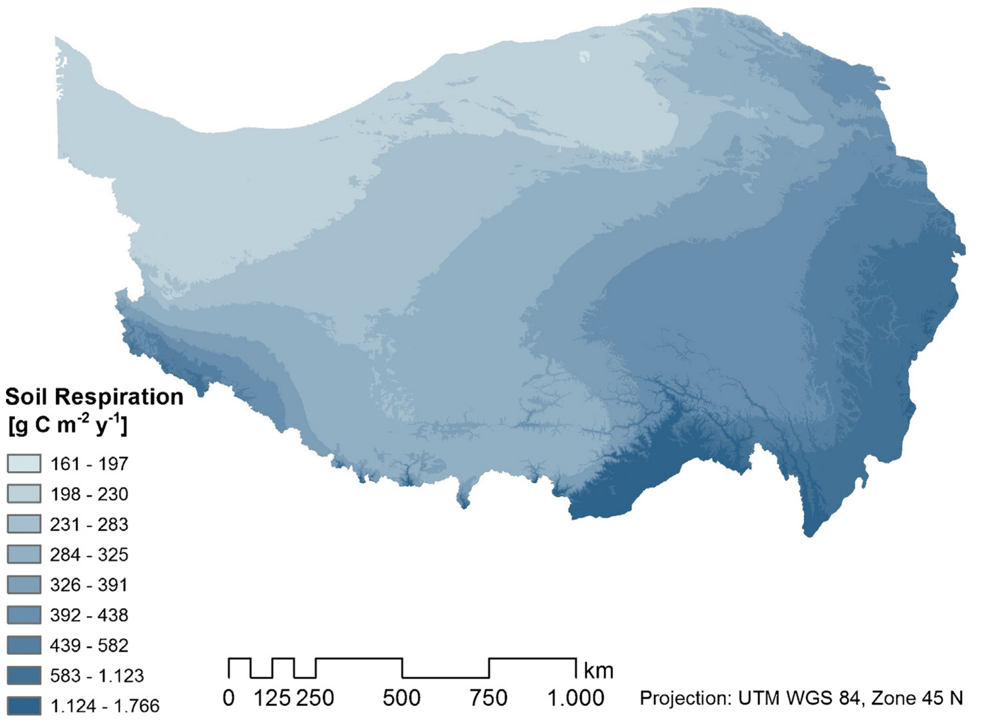

Fig. 4. Spatial distribution of soil respiration on the Qinghai-Tibet Plateau based on mean annual precipitation according to Raich and Schlesinger (1992). Soil respiration is in SI unit (Mg ha^{-1}). The spatial resolution of the grids is 1 × 1 km.

Please cite this article in press as: Bosch, A., et al., Predicting soil respiration for the Qinghai-Tibet Plateau: An empirical comparison of regression models. Pedobiologia - J. Soil Ecol. (2016), http://dx.doi.org/10.1016/j.pedobi.2016.01.002

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 comparision 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.

Acknowledgements

We thank the Ev. Studienwerk Villigst e.V. that funded this study conducted within the framework of the research project PERMATRANS. The support by the German Federal Ministry for Education and Research (BMBF, grant No. 03G0810A) is also acknowledged. We also thank Ji Luo (Institute of Mountain Hazards and Environment, Chinese Academy of Sciences and Ministry of Water Conservancy, Chengdu, China) for his support via messaging.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.pedobi.2016.01.002.

References

Amundson, R., 2001. The carbon budget in soils. Annu. Rev. Earth Planet. Sci. 29, 535–562.

Baumann, F., He, J.-S., Schmidt, K., Kühn, P., Scholten, T., 2009. Pedogenesis permafrost, and soil moisture as controlling factors for soil nitrogen and carbon contents across the Tibetan Plateau. Global Change Biol. 15, 3001–3017.

Baumann, F., Schmidt, K., Doerfer, C., He, J.-S., Scholten, T., Kühn, P., 2014. Pedogenesis permafrost, substrate and topography: plot and landscape scale interrelations of weathering processes on the central-eastern Tibetan Plateau. Geoderma 226–227, 300–316.

Behera, N., Joshi, S.K., Pati, D.P., 1990. Root contribution to total soil metabolism in a tropical forest soil from Orissa. India For. Ecol. Manag. 36, 125–134.

Böhner, J., Lehmkuhl, F., 2005. Environmental change modelling for Central and High Asia: Pleistocene, present and future scenarios. Boreas 34, 220–231.

Böhner, J., 2006. General climatic controls and topoclimatic variations in Central and High Asia. Boreas 35, 279–295.

Bond-Lamberty, B., Thomson, A., 2010a. Temperature-associated increases in the global soil respiration record. Nature 464, 579–582.

Bond-Lamberty, B., Thomson, A., 2010b. A global database of soil respiration data. Biogeosciences 7, 1915–1926.

Boone, R.D., Nadelhoffer, K.J., Canary, J.D., Kaye, J.P., 1998. Roots exert a strong influence on the temperature sensitivity of soil respiration. Nature 396, 570–572.

Bosch, A., Doerfer, C., He, J.-S., Schmidt, K., Scholten, T., 2016. A comparison of regression models to estimate belowground biomass on the Qinghai-Tibet Plateau. Catena (submitted 12.09.2015, CATENA4511) (unpublished results).

Cao, G., Tang, Y., Mo, W., Wang, Y., Li, Y., Zhao, X., 2004. Grazing intensity alters soil respiration in an alpine meadow on the Tibetan plateau. Soil Biol. Biochem. 36, 237–243.

Chapin III, F.S., Sturm, M., Serreze, M.C., McFadden, J.P., Key, J.R., Lloyd, A.H., McGuire, A.D., Rupp, T.S., Lynch, A.H., Schimel, J.P., Beringer, J., Chapman, W.L., Epstein, H.E., Euskirchen, E.S., Hinzman, L.D., Jia, G., Ping, C.-L., Tape, K.D., Thompson, C.D.C., Walker, D.A., Welker, J.M., 2005. Role of land-surface changes in Arctic summer warming. Science 310, 657–660.

Chen, X., Post, W., Norby, R., Classen, A., 2010. Modeling soil respiration and variations in source components using a multi-factor global climate change experiment. Clim. Change 1–22.

Chen, Y., Luo, J., Li, W., Dong, Y., She, J., 2014. Comparison of soil respiration among three different subalpine ecosystems on eastern Tibetan Plateau. China Soil Sci. Plant Nutr. 60, 231–241.

Cheng, G., 2005. Permafrost studies in the Qinghai-Tibet Plateau for road construction. J. Cold Reg. Eng. 19, 19–29.

Chimner, R.A., 2004. Soil respiration rates of tropical peatlands in Micronesia and Hawaii. Wetlands 24, 51–56.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.T., Laprise, R., Rueda, V.M., Mearns, L., Menéndez Räisänen, J., Rinke, A., Sarr, A., Whetton, P., 2007. Regional climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press Cambridge, pp. 848–940.

Curiel Yuste, J., Janssens, I.A., Carrara, A., Meiresonne, L., Ceulemans, R., 2003. Interactive effects of temperature and precipitation on soil respiration in a temperate maritime pine forest. Tree Physiol. 23, 1263–1270.

Da Silva, A.M., 2004. Rainfall erosivity map for Brazil. Catena 57, 251–259.

Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173.

Doerfer, C., Kuehn, P., Baumann, F., He, J.-S., Scholten, T., 2013. Soil organic carbon pools and stocks in permafrost-affected soils on the Tibetan Plateau. PLoS One 8 (2), e57024.

Duan, A.M., Wu, G.X., 2005. Role of the Tibetan Plateau thermal forcing in the summer climate patterns over subtropical Asia. Clim. Dyn. 24, 793–807.

Ewel, K.C., Cropper, W.P., Gholz, H.L., 1987. Soil CO_2 evolution in Florida slash pine plantations: II. Importance of root respiration. Can. J. For. Res. 17, 330–333.

Fan, J.-W., Shao, Q.-Q., Liu, J.-Y., Wang, J.-B., Harris, W., Chen, Z.-Q., Zhong, H.-P., Xu, X.-L., Liu, R.-G., 2010. Assessment of effects of climate change and grazing activity on grassland yield in the Three Rivers Headwaters Region of Qinghai-Tibet Plateau. China Environ. Monit. Assess. 170, 571–584.

Fang, C., Moncrieff, J.B., Gholz, H.L., Clark, K.L., 1998. Soil CO_2 efflux and its spatial variation in a Florida slash pine plantation. Plant Soil 205, 135–146.

Geng, Y., Wang, Y., Yang, K., Wang, S., Zeng, H., Baumann, F., Kuehn, P., Scholten, T., He, J.-S., 2012. Soil respiration in Tibetan alpine grasslands: belowground biomass and soil moisture, but not soil temperature, best explain the large-scale patterns. PLoS One 7, 1–12.

Hashimoto, S., Carvalhais, N., Ito, A., Migliavacca, M., Nishina, K., Reichstein, M., 2015. Global spatiotemporal distribution of soil respiration modeled using a global databse. Biogeosciences 12, 4121–4132.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Clim. 25, 1965–1978.

Immerzeel, W., Quiroz, R., Jong, S., 2005. Understanding precipitation patterns and land use interaction in Tibet using harmonic analysis of SPOT VGT-S10 NDVI time series. Int. J. Remote Sens. 26, 2281–2296.

Jia, B., Zhou, G., Wang, Y., Wang, F., Wang, X., 2006. Effects of temperature and soil water-content on soil respiration of grazed and ungrazed Leymus chinensis steppes, inner Mongolia. J. Arid Environ. 67, 60–76.

Jones, C.D., Cox, P.M., Essery, R.L.H., Roberts, D.L., Woodage, M.J., 2003. Strong carbon cycle feedbacks in a climate model with interactive CO_2 and sulphate aerosols. Geophys. Res. Lett. 30.

Joo, S.J., Park, S.-U., Park, M.-S., Lee, C.S., 2012. Estimation of SR using automatic chamber systems in an oak (*Quercus mongolica*) forest at the Nam-San site in Seoul, Korea. Sci. Total Environ. 416, 400–409.

Kang, S., Xu, Y., You, Q., Flügel, W.-A., Pepin, N., Yao, T., 2010. Review of climate and cryospheric change in the Tibetan Plateau. Environ. Res. Lett. 5, 1–8.

Koizumi, H., Konturi, M., Mariko, S., Nakadai, T., Bekku, Y., Mela, T., 1999. SR in thress soil types in agricultural ecosystems in Finland. Acta agriculturae scandinavic. Section B. Plant Soil 49, 65–74.

Kutzbach, J.E., Liu, X., Liu, Z., Chen, G., 2008. Simulation of the evolutionary response of global summer monsoons to orbital forcing over the past 280,000 years. Clim. Dyn. 30, 567–579.

Li, G., Sun, S., 2011. Plant clipping may cause overestimation of soil respiration in a Tibetan alpine meadow southwest China. Ecol. Res. 26, 497–504.

Liu, X., Chen, B., 2000. Climatic warming in the Tibetan Plateau during recent decades. Int. J. Clim. 20, 1729–1742.

Luo, T., Li, W., Zhu, H., 2002. Estimated biomass and productivity of natural vegetation on the Tibetan Plateau. Ecol. Appl. 12, 980–997.

Luo, T., Brown, S., Pan, Y., Shi, P., Ouyang, H., Yu, Z., Zhu, H., 2005. Root biomass along subtropical to alpine gradients: global implication from Tibetan transect studies. For. Ecol. Manag. 206, 349–363.

Luo, Y., Zhou, X., 2006. Soil Respiration and the Environment. Elsevier, San Diego.

Manabe, S., Terpstra, T., 1974. The effects of mountains on the general circulation of the atmosphere as identified by numerical experiments. J. Atmos. Sci. 31, 3–42.

Maussion, F., Scherer, D., Finkelnburg, R., Richter, J., Yang, W., Yao, T., 2011. WRF simulation of a precipitation event over the Tibetan Plateau, China—an assessment using remote sensing and ground observations. Hydrol. Earth Syst. Sci. 15, 1795–1817.

Miehe, G., Miehe, S., Böhner, J., Kaiser, K., Hensen, I., Madsen, D., Liu, J., Opgenoorth, L., 2014. How old is the human footprint in the world's largest alpine ecosystem? A review of multiproxy records from the Tibetan Plateau from the ecologists' viewpoint. Quat. Sci. Rev. 86, 190–209.

Morén, A.-S., Lindroth, A., 2000. CO_2 exchange at the floor of a boreal forest. Agric. For. Meteorol. 101, 1–14.

Pei, Z.-Y., Ouyang, H., Zhou, C.-P., Xu, X.-L., 2009. Carbon balance in an alpine steppe in the Qinghai-Tibet Plateau. J. Integr. Plant Biol. 51, 521–526.

Raich, J.W., Schlesinger, W.H., 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus 44B, 81–99.

Raich, J.W., Tufekcioglu, A., 2000. Vegetation and soil respiration: correlations and controls. Biogeochemistry 48, 71–90.

Reth, S., Reichstein, M., Falge, E., 2005. The effect of soil water content, soil temperature, soil pH-value and the root mass on soil CO_2 efflux—a modified model. Plant Soil 268, 21–33.

Rey, A., Pegoraro, E., Tedeschi, V., Parri, I.D., Jarvis, P.G., Valentini, R., 2002. Annual variation in SR and its components in a coppice oak forest in central Italy. Global Change Biol. 8, 851–866.

Rodeghiero, M., Cescatti, A., 2005. Main determinants of forest soil respiration along an elevation/temperature gradient in the Italian Alps. Global Change Biol. 11, 1024–1041.

Rodeghiero, M., Churkina, G., Martinez, C., Scholten, T., Gianelle, D., Cescatti, A., 2013. Components of forest soil CO_2 efflux estimated from $\Delta 14$C values of soil organic matter. Plant Soil 364/1, 55–68.

Schlesinger, W.H., Andrews, J.A., 2000. Soil respiration and the global carbon cycle. Biogeochemistry 48, 7–20.

Schroeder, P.E., Winjum, J.K., 1995. Assessing Brazil's carbon budget I. Biotic carbon pools. For. Ecol. Manag. 75, 77–86.

Singh, J.S., Gupta, S.R., 1977. Plant decomposition and soil respiration in terrestrial ecosystems. Bot. Rev. 43, 449–528.

Smith, E., Shi, L., 1995. Reducing discrepancies in atmospheric heat budget of Tibetan Plateau by satellite-based estimates of radiative cooling and cloud-radiation feedback. Meteorol. Atmos. Phys. 56, 229–260.

Valentini, R., Matteucci, G., Dolman, A.J., Schulze, E.-D., Rebmann, C., Moors, E., Granier, J., Gross, A., Jensen, P., Pilegaard, N.O., Lindroth, K., Grelle, A., Bernhofer, A., Grünwald, C., Aubinet, T., Ceulemans, M., Kowalski, R., Vesala, A.S., Rannik, T., Berbigier, Ü., Loustau, P., Guδmundsson, D., Thorgeirsson, J., Ibrom, H., Morgenstern, A., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S., Jarvis, P. G., 2000. Respiration as the main determinant of carbon balance in European forests. Nature 404, 861–865.

Wang, S., Jin, H., Li, S., Zhao, L., 2000. Permafrost degradation on the Qinghai-Tibet Plateau and its environmental impacts. Permafrost Periglacial Processes 11, 43–53.

Wang, W.Y., Wang, Q.J., Li, S.X., Wang, G., 2006. Distribution and species diversity of plant communities along transect on the Northeastern Tibetan plateau. Biodivers. Conserv. 15, 1811–1828.

Wang, B., Bao, Q., Hoskins, B., Wu, G., Liu, Y., 2008a. Tibetan Plateau warming and precipitation change in East Asia. Geophys. Res. Lett. 35.

Wang, C., Cao, G., Wang, Q., Jing, Z., Ding, L., Long, R., 2008b. Changes in plant biomass and species composition of alpine Kobresia meadows along altitudinal gradient on the Qinghai-Tibetan Plateau. Sci. China Ser. C 51, 86–94.

Wang, Y., Liu, H., Chung, H., Yu, L., Mi, Z., Geng, Y., Jing, X., Wang, S., Zeng, H., Cao, G., Zhao, X., He, J.-S., 2014. Non-growing-season soil respiration is controlled by freezing and thawing processes in the summer monsoon-dominated Tibetan alpine grassland. Global Biochem. Cycles 28, 1081–1095.

Wen, L., Dong, S., Li, Y., Wang, X., Li, X., Shi, J., Dong, Q., 2013. The impact of land degradation on the C pools in alpine grasslands of the Qinghai-Tibet Plateau. Plant Soil 368, 329–340.

Wiseman, P.E., Seiler, J.R., 2004. Soil CO_2 efflux across four age classes of plantation loblolly pine (*Pinus taeda* L.) on the Virginia Piedmont. For. Ecol. Manag. 192, 297–311.

Xu, Z.X., Gong, T.L., Li, J.Y., 2008. Decadal trend of climate in the Tibetan Plateau—regional temperature and precipitation. Hydrol. Process. 22, 3056–3065.

Yang, M., Wang, S., Yao, T., Gou, X., Lu, A., Guo, X., 2004. Desertification and its relationship with permafrost degradation in Qinghai-Xizang (Tibet) plateau. Cold Reg. Sci. Technol. 39, 47–53.

Yang, Y., Fang, J., Smith, P., Tang, Y., Chen, A., Ji, C., Hu, H., Rao, S., Tan, K.U.N., He, J.-S., 2009. Changes in topsoil carbon stock in the Tibetan grasslands between the 1980 and 2004. Global Change Biol. 15, 2723–2729.

Yang, Y., Fang, J., Tang, Y., Ji, C., Zheng, C., He, J.-S., Zhu, B., 2008. Storage: patterns and controls of soil organic carbon in the Tibetan grasslands. Global Change Biol. 14, 1592–1599.

Yu, H.Y., Luedeling, E., Xu, J.C., 2010. Winter and spring warming result in delayed spring phenology on the Tibetan Plateau. Proc. Natl. Acad. Sci. U. S. A. 107, 22151–22156.

Zhang, Y., Li Bingyuan, Du, Z., 2002. The area and boundary of Qinghai-Tibet Plateau. Geog. Res. 21, 1–8 (in Chinese).

Zhang, Y., Ohata, T., Kodata, T., 2003. Land-surface hydrological processes in the permafrost region of the eastern Tibetan Plateau. J. Hydrol. 283, 41–56.

Zhang, X., Shi, P., Liu, Y., Ouyang, H., 2005. Experimental study on soil CO_2 emission in the alpine grassland ecosystem on Tibetan Plateau. Sci. China Ser. D 48, 218–224.

Zhang, Y., Tang, Y., Jiang, J., Yang, Y., 2007. Characterizing the dynamics of soil organic carbon in grasslands on the Qinghai-Tibetan Plateau. Sci. China Ser. D 50, 113–120.

Zhang, P., Tang, Y., Hirota, M., Yamamoto, A., Mariko, S., 2009. Use of a regression method to partition sources of ecosystem respiration in an alpine meadow. Soil Biol. Biochem. 41, 663–670.

Zhang, Y., Wang, G., Wang, Y., 2010. Response of biomass spatial pattern of alpine vegetation to climate change in permafrost region of the Qinghai-Tibet Plateau, China. J. Mt. Sci. 7, 301–314.

Zheng, D., 1996. The system of physico-geographical regions of the Qinghai-Xizang (Tibet) Plateau. Sci. China Ser. D 39, 410–417.

Zhong, L., Ma, Y., Salama, M.S., Su, Z., 2010. Assessment of vegetation dynamics and their response to variations in precipitation and temperature in the Tibetan Plateau. Clim. Change 103, 519–535.

Zhuang, Q., He, J., Lu, Y., Ji, L., Xiao, J., Luo, T., 2010. Carbon dynamics of terrestrial ecosystems on the Tibetan Plateau during the 20th century: an analysis with a process-based biogeochemical model. Global Ecol. Biogeogr. 19, 649–662.

Please cite this article in press as: Bosch, A., et al., Predicting soil respiration for the Qinghai-Tibet Plateau: An empirical comparison of regression models. Pedobiologia - J. Soil Ecol. (2016), http://dx.doi.org/10.1016/j.pedobi.2016.01.002