Environmental Earth Sciences (2018) 77:247
https://doi.org/10.1007/s12665-018-7424-4

ORIGINAL ARTICLE

Soil organic carbon within the vadose zone of a floodplain

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Received: 6 October 2017 / Accepted: 16 March 2018 / Published online: 22 March 2018

Abstract

Past studies have focused on carbon variation in the upper 1 m of the soil profile. However, there is limited information on carbon variation at deeper depths (e.g., 0–4 m) and mathematical functions to extrapolate carbon content at these depths. The objective of this study was therefore to assess the vertical variation in SOC (reached 4 m) of the Tarim River floodplain in northwestern China. The vertical distribution in SOC was described by exponential and power functions based on (1) soil depth, (2) soil depth and silt content, (3) soil depth and SOC at the shallowest and deepest depths, (4) soil depth, silt content, and SOC at the shallowest and deepest depths, and (5) soil depth and SOC at the shallowest depth. We found SOC content decreased with depth from 6.82 g kg^{-1} at 0–0.2 m to < 1.0 g kg^{-1} below 3.2–3.4 m averaged across five locations along the floodplain. Both the power and exponential functions provided a good fit to the measured data in the upper 1 m of the soil profile, whereas the power function provided a better fit to the data when extrapolating to a depth of 3–4 m. The power function describing SOC as a function of soil depth, silt content, and SOC at the shallowest and deepest depths best portrayed the distribution in SOC with depth. Considering the cost and labor in measuring soil properties, our results suggest that SOC at the shallowest depth can provide good estimates of the vertical distribution in SOC in a floodplain.

Keywords Soil profile · Soil texture · Tarim River

Introduction

The floodplains of rivers are among the most dynamic, diverse, and productive ecosystems on earth (Keddy 2000). The riverine floodplains cover $> 2 \times 10^6$ km^2 in the world (Tockner and Stanford 2002). Floodplain soils contain large stocks of organic carbon (Batjes 1996; Cierjacks et al. 2011; Ricker et al. 2013; Zehetner et al. 2009) which underlie the significance of floodplain soils in regional and global carbon cycles. Yet, there is a need to understand the dynamics of soil organic matter or SOC in these ecosystems (Mitra et al. 2005; Rieger et al. 2013).

Several studies have demonstrated that particulate organic material in floodplains is deposited during floods (Adair et al. 2004; Thoms 2003). This material has the potential to add to the pool of soil nutrients (Adair et al. 2004). The frequency of flooding (Bernal and Mitsch 2008) and carbon-rich sediments usually increase SOC stocks in the soil profile (Cierjacks et al. 2010; Wohl et al. 2012). The dynamics of organic carbon in floodplain soils are not only dependent on the input of organic matter, but also stabilization of organic matter against mineralization (Bernal and Mitsch 2008). Estimation of SOC in the floodplain could improve our understanding of carbon distribution at watershed and regional scales (Ricker and Lockaby 2015).

SOC stocks are important for assessing ecosystem services (Maes et al. 2016), but current assessments often consider only the topsoil (Ottoy et al. 2017). Therefore, the distribution of SOC at lower depths as well as the effectiveness of management strategies should be considered (Govers et al. 2013). Many studies that focus on carbon dynamics in soils generally account for carbon stocks in the upper 1 m of the profile (Jobbagy and Jackson 2000). However, sampling the vadose zone and an assessment of carbon storage at depths > 1 m can be equally or of greater importance in

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floodplain ecosystems (Carter et al. 2009; Izaurralde et al. 2007; Zehetner et al. 2009). As a result, SOC stocks in subsoils should not be neglected in an ecosystem service context (Ottoy et al. 2017). The scarcity of SOC data below 1 m constraints estimates on deeper carbon pools (Jobbagy and Jackson 2000). Ottoy et al. (2017) pointed out that vertical extrapolation of the topsoil measurement is often necessary. Lin (2003) suggested that soil scientists have traditionally limited their investigations to the upper few meters beneath the earth's surface with greater emphasis on the root zone. Emphasis on sampling carbon in the upper soil profile neglects the importance of hydropedology in regulating soil carbon.

The characterization of the vertical distribution in SOC in the near surface using mathematical functions can be extrapolated to deeper depths (Bennema 1974; Bernoux et al. 1998; Jobbagy and Jackson 2000; Spycher et al. 1983) to improve estimates of SOC budgets (Jobbagy and Jackson 2000). Existing studies (Bennema 1974; Bernoux et al. 1998; Jobbagy and Jackson 2000; Spycher et al. 1983) provide mathematical functions of the vertical distribution of SOC. Although these mathematical functions vary widely in form, the exponential function is the most widely accepted (Mestdagh et al. 2004; Minasny et al. 2006; Mishra et al. 2009; Zinn et al. 2005). Bennema (1974) found that a power function adequately described the decrease in carbon with depth, while Zinke et al. (1978) found the cumulative log–log model best described the vertical distribution in SOC.

The vertical distribution of SOC is dependent on several variables (Bullinger-Weber et al. 2014). For example, the vertical distribution of SOC has been related to soil texture (Zinn et al. 2005) or to SOC at the shallowest and deepest depths in the soil profile (Arrouays and Pelissier 1994; Bernoux et al. 1998; Hilinski 2001). However, variables to predict the vertical distribution in SOC are costly and time consuming to acquire, particularly in deep soils. Therefore, simple functions with few variables are sought to describe the vertical distribution in SOC.

The Tarim River Basin is a typical inland river. Located in the Tarim Basin in northwest China, the basin is one of the largest arid zones and may be one of the most fragile ecological environments in the world (Chen et al. 2006, 2010, 2011; Hao et al. 2010; Li et al. 2013a, 2016). Periodic overflow along the river plays an important role in maintaining spatial heterogeneity in plant community composition and structure in arid floodplain (Blom and Voesenek 1996). River overflow, which can encompass 3000–5000 km^2 of land (Song et al. 2000a, b), may also contribute to changes in soil profile characteristics and vegetation cover along the Tarim River. Planned or regulated river overflow was devised to rehabilitate and reverse ecosystem degradation (Wuethrich 1996). River overflow is regulated through 49 ecology gates which were constructed along the Tarim River in 2005 (Huang et al. 2015). The purpose of the ecology gates was to maintain native vegetation along the middle and lower reaches of the river. The Chinese government has invested over 10^{10} yuan (RMB) since 2000 to harness the Tarim River for ecological restoration (Xu et al. 2009).

The purpose of this study was to examine the vertical distribution of SOC along the Tarim River floodplain and to identify mathematical functions that adequately portray the vertical distribution of SOC within the vadose zone.

Materials and methods

Study area

Our study was conducted along the Tarim River which is located in the Xinjiang Uygur Autonomous Region of China. The Tarim River is the largest inland river in China flowing through the Taklimakan Desert and lies in the Tarim River Basin with an area of 1.22 million km^2. A continental climate typifies this arid region. The annual precipitation varies from 20 to 50 mm, and rainfall reaches its maximum in July and August. The annual potential evaporation varies from 2500 to 3000 mm, and annual sunshine varies from 2500 to 3550 h. The annual mean temperature varies from − 11.5 to 10.6 °C. Temperatures reach a maximum in July with an extreme maximum temperature of 43.6 °C.

The Tarim River has an overall length of 1321 km. The main source of water for the river is precipitation and glacial melt water from mountain headstreams, the latter of which accounts for 48.2% of the total water volume (Song et al. 2000a, b). Snow melt largely contributes to the springtime runoff of the Tarim River. Later, during summer, when temperatures in the high mountains have risen, runoff of glacier melt water largely contributes to the Tarim River. Three quarters of the runoff that contributes to the river occur in the summer, so summer floods along the river are not uncommon (Fan et al. 2016).

Sediment accumulation, meandering channels, river overflow, and environmental deterioration are of great concern in the Tarim River Basin (Hu et al. 2005). The river is relatively wide (500–1200 m) and straight (little meandering) from Alaer to Shaya (Wang et al. 2009a). Further downriver from Shaya to Yingbazha, the river maintains a width of 500–1000 m but transitions to meandering channels with a bending coefficient of 1.75. The river is 200–500 m wide and has a bending coefficient of 1.68 from Yingbazha to Aqike, while the river is 50–300 m wide with a bending coefficient of 2.0 from Aqike to Yingsu (Shan and Nuerbayi 2007). The river flows from west to east with fluvial geomorphic units classified as alluvial plain, river valley geomorphology, and sand dunes (Li et al. 2005). The alluvial plain was mainly located in flat areas on both sides of the river, while aeolian deposits were located to the south of the river (Li et al. 2005). Sediment content carried by the river decreased from 5.07 to 0.20 kg m^{-3} from Alaer to Yingsu (Hu et al. 2005). Soil types that occur along the river were aeolian sand, meadow soil, and solonchak. Growth of natural vegetation along the river is sustained by both floods and groundwater recharge (Song et al. 2000a, b). In 2000, the groundwater table varied from 3.08 m in the upper reach of the river to 8.20 m in the lower reach of the river. Xu et al. (2003) reported that the groundwater table rose from 8.50 to 3.79 m after flooding in the lower reach of the Tarim River. Native vegetation in the floodplain of the river consisted of woodlands (dominated by Populus euphratica), shrubs (Tamarix spp., Lycium ruthenicum, and Halimodendron halodendron), and herbs (Phragmites australis, Apocynum venetum, Alhagi sparsifolia, Karelinia caspica, and Glycyrrhiza inflata) (Xu et al. 2009).

Soil samples

Soil samples were collected at five locations along the Tarim River. Our intent was not to characterize the variation in SOC at equidistant positions along the length of the river, but to characterize the vertical distribution in SOC with depth at key locations along the river. The locations (Fig. 1) were near Alaer, Shaya, Yingbazha, Aqike, and Yingsu and are part of a long-term hydrology and ecology monitoring network (Chen et al. 2013; Song et al. 2000a, b). The Alaer and Shaya locations were in the upper reach of

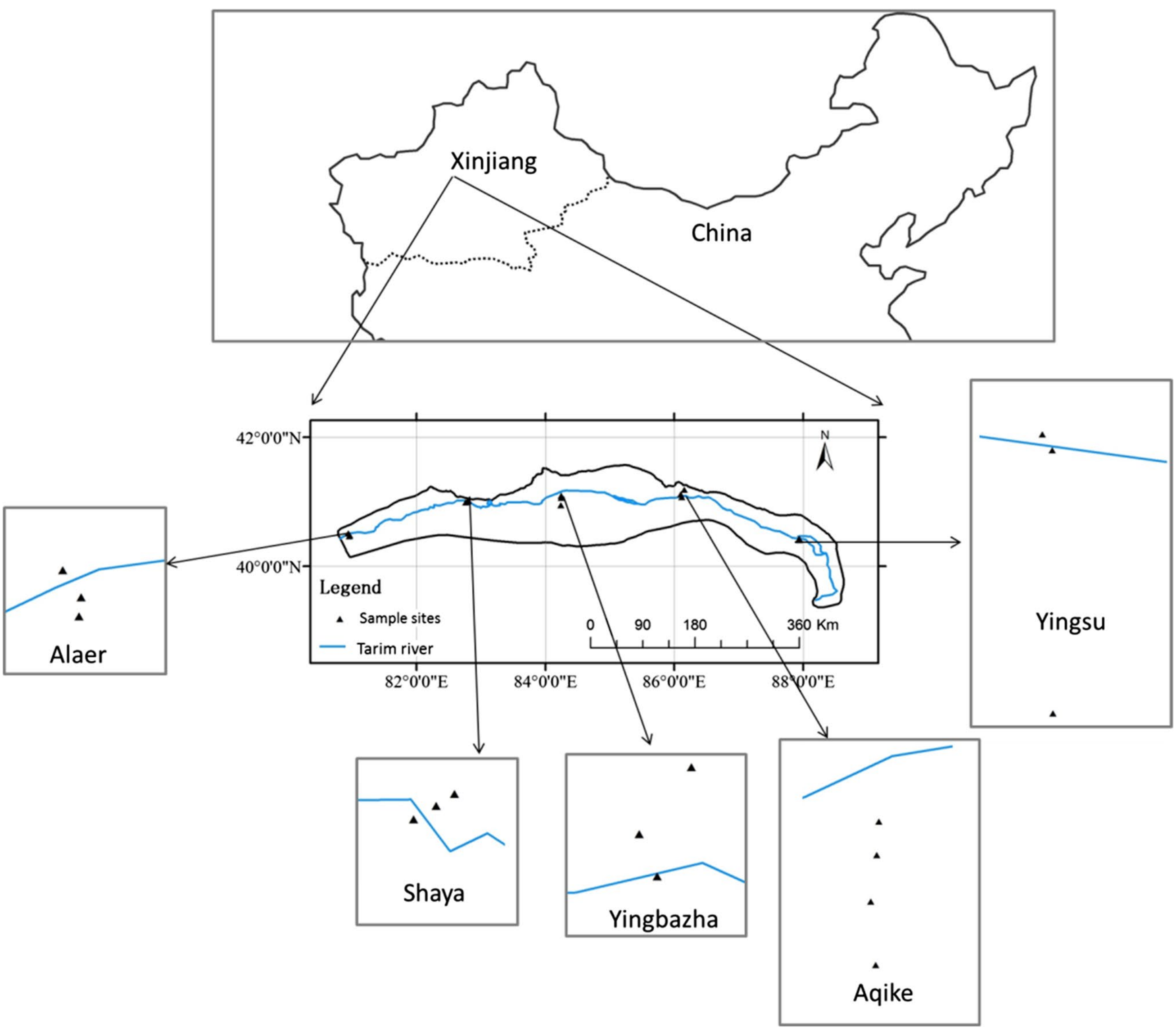

Fig. 1 Soil sample locations near cities along the floodplain of the Tarim River in Xinjiang Province of China

the Tarim River where there was great sediment accumulation (Shan and Nuerbayi 2007); these two locations were near two national hydrology stations (Alaer and Xinqiman hydrology stations). The Yingbazha and Aqike locations were in the middle reach of the river and were located in an area of serious flooding. Water flow through this area was 23.99×10^8 m^3 of annual flow (1957–1999) and accounted for 43.5% of total water volume (Wang et al. 2003). The Yingsu location was in the lower reach of the river where there is serious environmental deterioration (Chen et al. 2010; Hao et al. 2006; Xu et al. 2003).

At each location, samples were taken from three to four soil profiles located at various distances perpendicular to the Tarim River (Table 1). The dominate vegetation in the vicinity of all soil profiles was Populus euphratica; this vegetation plays an important role in the ecological balance of the Tarim River Basin and protects the oases in this basin (Chen et al. 2011). Soil samples were collected in October 2010, about 3 months after the last flood. The depth of soil sampling was to groundwater. Massive natural flooding occurred along the river in July 2010 with peak flow rates of 1500 m^3 s^{-1}. This flow rate was the largest to have occurred in the past 11 years. Three or four soil profiles were chosen for sampling at each location based upon similarity in vegetation and exposure to flooding. Since vegetation is an important factor which influences SOC storage (Jobbagy and Jackson 2000), particularly along the Tarim River (Yang et al. 2009), soil profiles at each location were selected with similar vegetation characteristics. The five locations used in our study were chosen based on several criteria: proximity to monitoring stations where research is being conducted on hydrology, metrology, and biomass; proximity to forestland dominated by Populus euphratica; and distance along the Tarim River.

Soil samples were collected at 0.2-m depth intervals in each soil profile, beginning at the soil surface and ending at the depth of ground water. Soil samples were obtained using a portable electric drill (Model HM1801, MAKITA) (Fig. 2). This apparatus was used to extract 0.1-m-diameter soil cores to the depth of groundwater. One soil profile core sample was taken at each site per location. The 2–3-kg soil samples (0.2 m long by 0.1 m diameter) were air-dried and then hand-sifted through a 2-mm sieve to remove stones and plant residue. Soil aggregates larger than 2 mm were mechanically fractured to facilitate passage through the 2-mm sieve.

Soil analysis

Particle size distribution was measured using a Malvern Mastersizer S laser diffractometer (Malvern Instrument, Malvern, England). The diffractometer measures volume percentage of particles in 100 size classes from 0.02 to 2000 μm. Samples were pretreated prior to analysis using sodium acetate to dissolve carbonates and hydrogen peroxide to oxidize organic matter. Samples were rinsed with deionized water, centrifuged, and excess supernatant was decanted. Each sample was dispersed with sodium hexametaphosphate by agitation for 16 h and analyzed in a deionized water suspension with no sonication. Soil texture described in this paper denotes percent clay (< 2 μm), silt (2–50 μm), and sand (50–2000 μm) following the taxonomy of the U.S.

Table 1 Soil sample sites along the Tarim River of northwestern China

Locations	Soil profile	Latitude	Longitude	Soil depth (m)	Distance from river (km)
Alaer	1	80.9568	40.48612	3.0	2.4
	2	81.81269	40.74178	3.0	1.1
	3	81.81583	40.73944	3.0	1.4
Shaya	1	82.76972	40.99583	4.0	1.5
	2	82.7897	41.00795	3.0	0.6
	3	82.81083	41.02139	3.0	2.6
Yingbazha	1	84.24699	40.95151	4.0	8.4
	2	84.25018	41.09791	4.0	11.5
	3	82.76972	40.99583	4.0	22.3
Aqike	1	86.10465	41.12016	4.0	5.5
	2	86.12228	41.07868	4.0	7.5
	3	86.15667	41.18861	4.0	15.6
	4	86.15712	41.18864	4.0	16.5
Yingsu	1	87.93917	40.43167	3.0	6.64
	2	87.93999	40.41029	3.0	3.96
	3	87.94010	40.43092	4.0	3.08

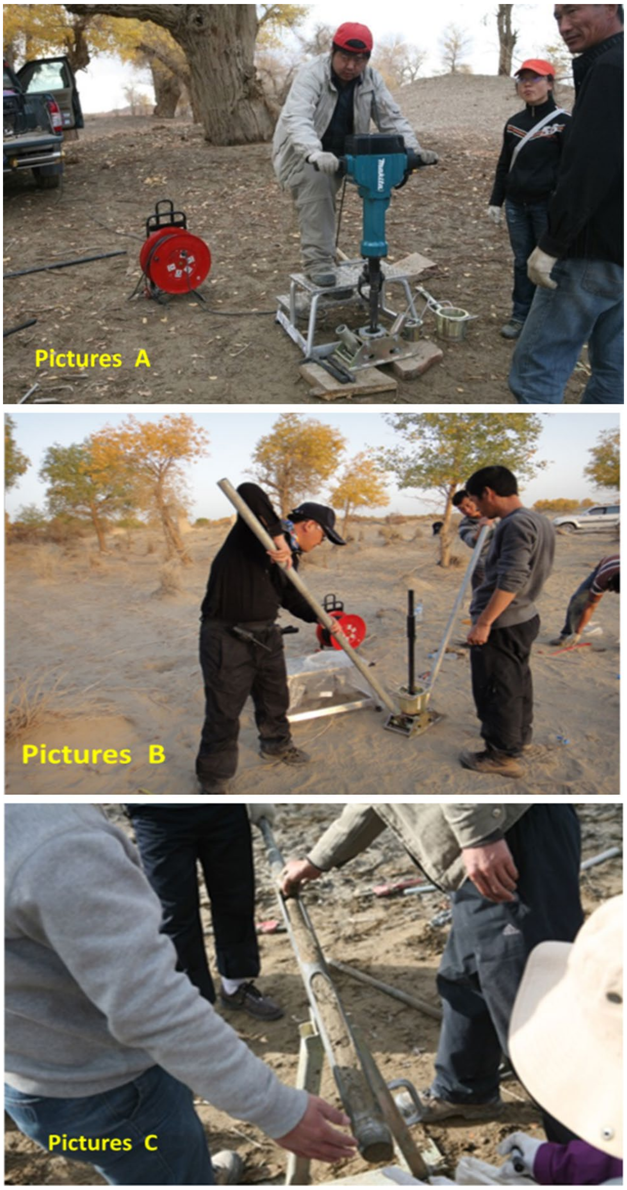

Fig. 2 Equipment used to extract cores from the soil profile along the floodplain of the Tarim River. An electric drill was used to drive the sampling tube into the soil profile (**a**), the tube was extracted using a jack (**b**), and the soil sample extracted by hand from the tube (**c**)

Department of Agriculture. Organic C content of samples was determined using the Walkley–Black procedure (Allison 1965). Briefly, organic matter in soil samples was oxidized using a 1 N $K_2Cr_2O_7$ solution. The reaction is assisted by the heat generated when two volumes of H_2SO_4 are mixed with one volume of the dichromate. The remaining dichromate is titrated with ferrous sulfate. The titrate is inversely related to the amount of carbon present in the soil sample.

Estimation of SOC vertical distribution

The vertical distribution of SOC in the soil profile was portrayed using mathematical functions as shown in Table 2. Minasny et al. (2006), Mishra et al. (2009), and Zinn et al. (2005) used an exponential function to describe the vertical distribution in SOC (E1 in Table 2), while Bennema (1974) found a power function adequately described the vertical distribution of SOC in the soil profile (P1 in Table 2). The vertical distribution of SOC was also described as power and exponent functions of soil depth and silt content (E2 and P2 in Table 2). Hilinski (2001) described SOC as an exponential function of soil depth and SOC at the shallowest and deepest depths in the profile (E3 in Table 2). A similar expression to express the vertical distribution in SOC was used, but with a power function (P3 in Table 2). Furthermore, the vertical distribution in SOC was described as power and exponential functions of soil depth, silt content, and SOC content at the shallowest and deepest depths in the soil profile (E4 and P4 in Table 2) or soil depth and SOC at the shallowest depth (E5 and P5 in Table 2). The functions were fit using SPSS 20 for windows.

The performance of these functions in estimating SOC at depth was evaluated using the root-mean-square error (RMSE)

$$\mathrm{RSME} = \sqrt{\frac{\sum_{i=0}^{n}(p-m)^2}{n}} \tag{1}$$

where p was calculated value, m was observed value, and n is the number of observations. A lower RMSE indicates better model performance.

Table 2 Power and exponential functions used to predict vertical distribution in soil organic carbon

No.[a]	Power function[b]	No.	Exponential function
E1	$\mathrm{SOC_Z} = a\mathrm{EXP}^{(-kz)}$	P1	$\mathrm{SOC_Z} = aZ^{(-k)}$
E2	$\mathrm{SOC_Z} = (aC_Z + b)\mathrm{EXP}^{(-kz)}$	P2	$\mathrm{SOC_Z} = (aC_Z + b)Z^{(-k)}$
E3	$\mathrm{SOC_Z} = C_b + (C_0 - C_b)\mathrm{EXP}^{(-kz)}$	P3	$\mathrm{SOC_Z} = C_b + a(C_0 - C_b)Z^{(-k)}$
E4	$\mathrm{SOC_Z} = C_b + (aC_Z + b)(C_0 - C_b)\mathrm{EXP}^{(-kZ)}$	P4	$\mathrm{SOC_Z} = C_b + (aC_Z + b)(C_0 - C_b)z^{(-k)}$
E5	$\mathrm{SOC_Z} = aC_0\mathrm{EXP}^{(-kZ)}$	P5	$\mathrm{SOC_Z} = aC_0Z^{(-k)}$

[a]E represents an exponential function and P represents a power function

[b]Parameters include: SOC is soil organic carbon, z is soil depth (m), C_Z is silt content (%), C_0 is SOC at the shallowest depth, (C_b) is SOC at the deepest depth, and a, b, and k are fitted parameters

Results and discussion

Distribution of soil organic carbon with depth

Soil organic carbon content ranged from 0.47 to 13.44 g kg^{-1} and had a mean value of 2.04 g kg^{-1} (SE, standard error of 0.10 g kg^{-1}) across all depths and locations. The top soil (0–0.2 m) had the highest SOC content, which ranged from 2.17 to 13.44 g kg^{-1} with a mean value of 6.82 g kg^{-1}(SE of 0.75 g kg^{-1}) across all locations. Soil organic carbon content displayed a decrease with soil depth; the soil at 0.2–0.4 depth had a SOC content of 3.64 g kg^{-1} (SE of 0.45 g kg^{-1}), whereas SOC content at a depth of 0.4–0.6 m was 2.77 g kg^{-1} (SE of 0.36 g kg^{-1}) (Fig. 3). The SOC content was < 1.0 g kg^{-1} at 3.4 m (Fig. 3). Previous studies showed that the SOC generally decreases with depth (Oades 1995; Spain 1990) due to the addition of C to the soil surface (Alvarez and Lavado 1998). Mishra et al. (2009) also found that the

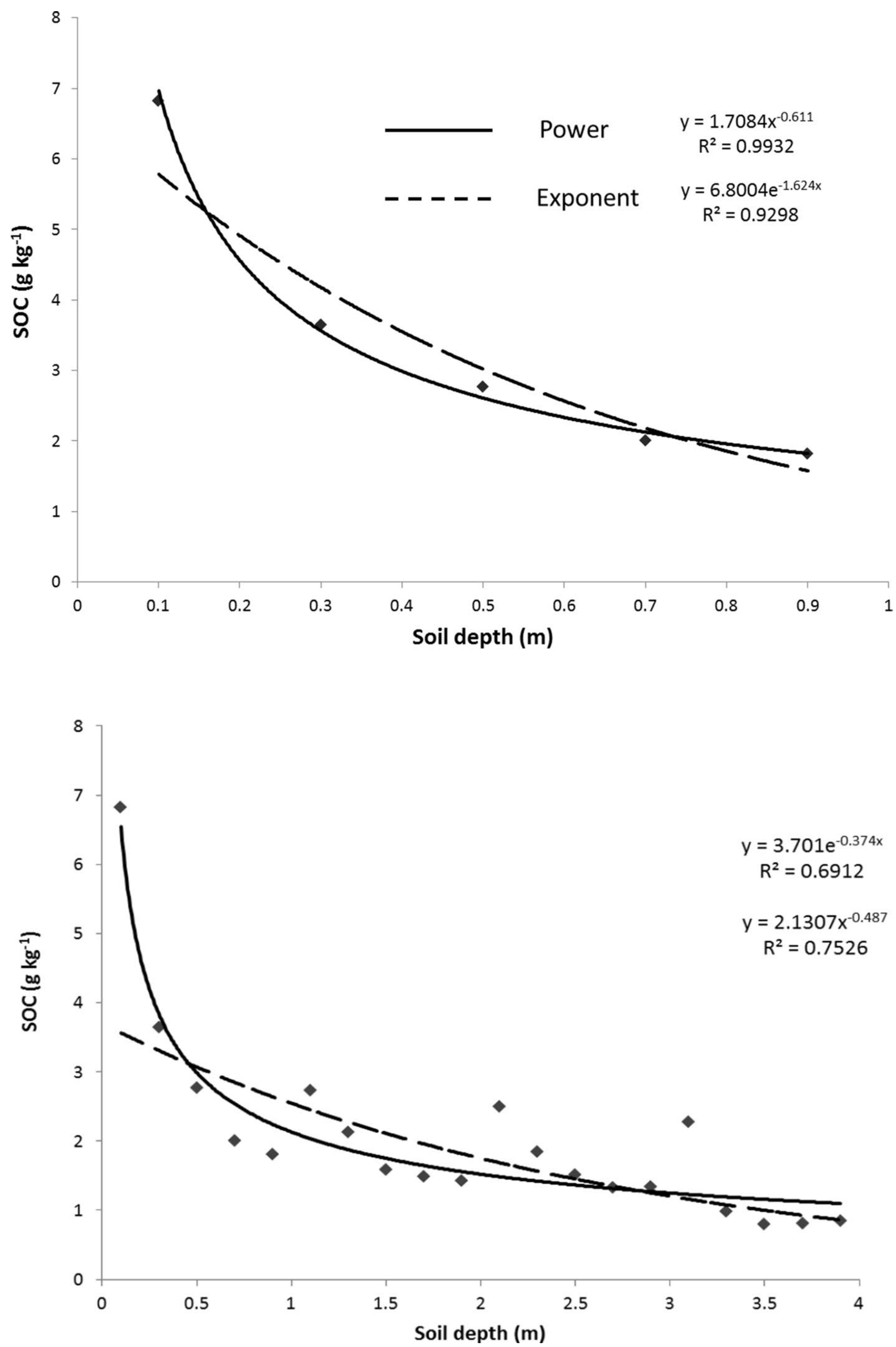

Fig. 3 The variation in soil organic carbon (SOC) content with soil depth. Each point represents SOC content averaged across all soil profiles and locations along the floodplain

SOC was mainly stored in top soil. Ricker and Lockaby (2015) reported that soil C concentration constantly decreased with depth along the Congaree River floodplain in South Carolina, USA. They found the soil C concentration decreased from 2.2% near the surface to < 0.4% at 2.0 m depth. Wang et al. (2009b) also found the averaged soil carbon content at 0.2 m (approximately the A horizon) was 0.42% and quickly dropped below 0.1% at depths greater than 1 m in the Nebraska Sand Hills. A possible reason for the large difference in soil C concentration with depth was the difference in the physical and chemical characteristics between the surface and subsoil (Holden and Fierer 2005). Both moisture and temperature are highly variable at the soil surface, but this variability generally decreases with depth in the vadose zone (Fierer et al. 2003; Hendry et al. 1999; Hillel 1980; Jury et al. 1991). Another reason for the large decrease in SOC with depth may be due to the addition of C to the soil surface (Alvarez and Lavado 1998). Decay of above-ground vegetation results in the accumulation of organic material on the soil surface (Oades 1995; Spain 1990), thereby enhancing SOC at the surface of floodplain soils along the Tarim River (Yang et al. 2009). Jobbagy and Jackson (2000) reported that vegetative production and decomposition determine C inputs to the soil profile. Furthermore, biomass allocation above and below ground and between shallow and deep roots influences the relative distribution of soil carbon with depth. Soil organic carbon content is inversely proportional to soil bulk density (Federer et al. 1993; Saini 1966); thus, higher bulk density at depth along the lower reach of the Tarim River (Wang et al. 2016) suggest that SOC decreases with depth.

Periodic flooding may also contribute to depth variations in SOC. Jones and Smock (1991) reported that during flooding much of the particulate organic matter (POM) moved from the channels onto the floodplains. Jelinski and Kucharik (2009) and Shrestha et al. (2012) also reported that flooding has a positive influence on soil nutrition. Floodplains alter the quantity and composition of organic matter (Cuffney 1988) through retention and transformation (Admiraal and Vanzanten 1988). Hydrological connectivity can be expected to influence the relative importance of autochthonous and allochthonous sources of POM in riverine floodplains (Pinay et al. 2000). Robertson et al. (1999) reported that large pools of POM exist on floodplains as litter (> 500 g C m^{-2}) and coarse woody debris (~ 6 kg C m^{-2}). In addition, sediments deposited on floodplains during floods represent a substantial sink of riverine POM (up to 280 g C m^{-2}). Shen et al. (2006) reported that the Tarim River flooded 1.74 times every year during the period from 1951 to 2000. Flood peaks greater than 800 m^3 s^{-1} occurred in almost every year from 2000 to 2006 and those greater than 1000 m^3 s^{-1} occurred in six of these 7 years (Chen et al. (2011). This frequency of flooding may lead to more POM in the upper soil profile.

Jobbagy and Jackson (2000) reported that SOC at a 2–3 m depth in shrubland was 77% of that in the 0–1 m depth, whereas in forests and grasslands, SOC at a depth of 2–3 m was 56 and 43%, respectively, of that in the uppermost meter of the profile. Our results suggest the mean SOC content was 3.41 g kg^{-1} at 0–1 m depth, 1.87 g kg^{-1} at 1–2 m depth, 1.70 g kg^{-1} at 2–3 m depth, and 1.14 g kg^{-1} at the 3–4 m depth. Thus, SOC at 1–2, 2–3, and 3–4 m depths was 54.8, 49.9, and 33.4% of that in the first meter of the soil profile. Figure 3 shows a steep decrease in SOC in the upper part of the soil profile. Jobbagy and Jackson (2000) pointed out that the relative SOC content in the second and third meters of the soil profile was higher in shrublands than forests, whereas SOC decreased sharply in the upper soil profile in forestland.

Previous studies suggest that distribution of organic matter in the soil is positively associated with clay content (Burke et al. 1989; Spain et al. 1983). Some studies, however, showed no significant relationship between SOC and soil texture (Hontoria et al. 1999), while other studies reported a good relationship between SOC and silt plus clay (Rantoa et al. 2015; Zinn et al. 2005). Zinn et al. (2005) considered that SOC was linearly correlated with silt plus clay, but not to clay content. Wang et al. (2009b) reported a good relationship between SOC and silt ($R = 0.581$). In this study, soil texture ranged from sand to silt loam (Fig. 4). We found a negative relationship between SOC and sand ($R^2 = 0.280$) and a positive relationship between SOC and silt ($R^2 = 0.289$), clay ($R^2 = 0.189$), and silt plus clay ($R^2 = 0.280$) (Fig. 5).

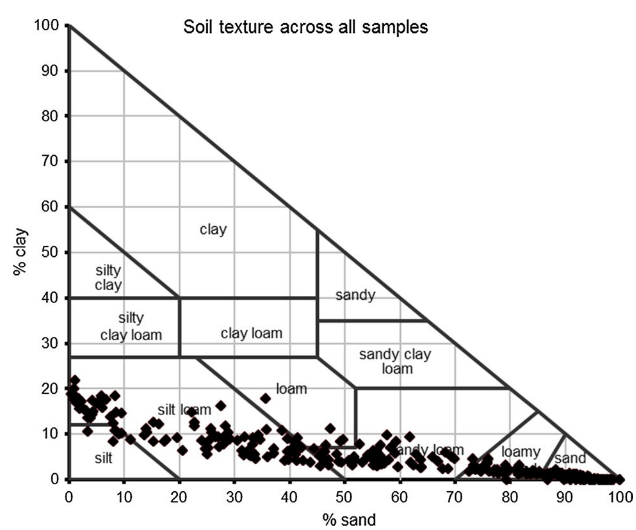

Fig. 4 The soil texture across all soil samples

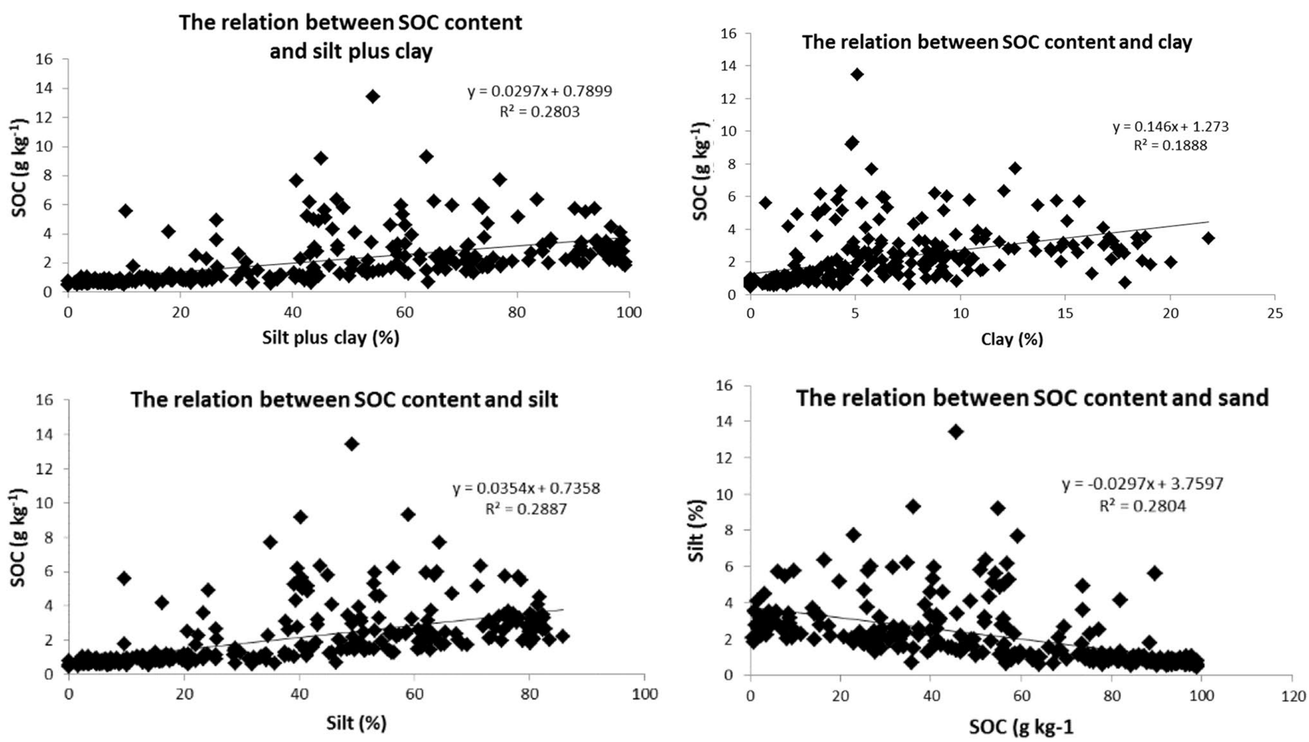

Fig. 5 The relation between soil organic carbon (SOC) content and clay, clay plus silt, silt, and sand content. Each point represents one sampling depth from one profile at one location

Estimation of SOC with depth

The vertical distribution of organic carbon content in the soil profile can be expressed by an exponential (Webster 1978; Zinn et al. 2005) or power function (Bennema 1974). An exponential and power function was fit to our observations, the results of which are reported in Table 3 and Fig. 6. The functions E1 and P1 in Table 3 are, respectively, the exponential and power functions relating SOC to soil depth. The power function provided a better fit to the data (lower RMSE and higher R^2). However, the fit of the power function was not very good as R^2 was 0.317 for the 0–1 m depth. The main reason for both functions poorly fitting the data is that SOC is influenced by many factors such as soil texture or flooding. Flooding can result in the deposition of sediment and the subsequent burial of the previously exposed surface. This depositional process can therefore result in an irregular decrease in soil carbon with depth.

SOC as a function of depth and soil texture

Zinn et al. (2005) found SOC was an exponential function of silt plus clay content, whereas Parton et al. (1987) and Burke et al. (1989) found SOC stocks over a wide climatic gradient could be predicted from clay plus silt, clay, or silt content. Therefore, the relationship between SOC and silt content was examined using both the power and exponential functions (E2 and P2 in Table 3). Based upon a reduction in the RMSE and increase in R^2, SOC was better predicted as a function of depth and silt content (Fig. 7) than depth alone (Fig. 6). Silt content was a better predictor of the vertical distribution in SOC than silt plus clay or clay content. For example, exponential and power functions describing the relationship between SOC and depth and silt plus clay content in a 4 m profile had a respective R^2 of 0.400 and 0.453. Likewise, exponential and power functions describing the relationship between SOC and depth and clay content in a 4 m profile had a respective R^2 of 0.360 and 0.409. Silt may be more influential to the vertical distribution of SOC than silt plus clay or clay because flood waters contain large amounts of silt. Hu et al. (2005) reported that the particle diameter of the suspended load in flood waters ranged from 2 to 50 μm in the Tarim River. They also found the D50 (50th percentile of the particle size distribution) of the suspended load ranged from 11 to 41 μm in upper reach of the river, while the D50 was 31 μm in middle reach of the river. Zhou et al. (2010) observed that near-surface silt content of floodplain soils increased by 37.3%, whereas clay content increased by 3.0% after flooding in the Tarim River.

Table 3 The performance of functions to predict vertical distribution in soil organic carbon

Depth	No.[a]	Parameters			RMSE[b]	R^2	No.	Parameters			RMSE	R^2
(m)		*a*	*b*	*k*	g kg^{-1}			*a*	*b*	*k*	g kg^{-1}	
0–1	E1	5.7123		1.395	2.00	0.300	P1	1.5537		0.714	1.96	0.317
0–2		3.8400		0.623	1.79	0.244		1.8305		0.556	2.39	0.284
0–3		3.0673		0.363	1.67	0.191		1.9325		0.469	1.56	0.245
0–4		3.3182		0.361	1.75	0.285		2.0534		0.545	1.64	0.309
0–1	E2	0.063	3.554	1.359	1.83	0.420	P2	0.020	1.031	0.600	1.80	0.428
0–2		0.057	1.931	0.591	1.54	0.396		0.028	0.982	0.462	1.47	0.451
0–3		0.052	1.459	0.344	1.38	0.408		0.032	0.967	0.390	1.31	0.473
0–4		0.056	1.782	0.341	1.48	0.419		0.035	1.105	0.420	1.41	0.476
0–1	E3			2.072	1.32	0.668	P3	0.093		1.485	1.12	0.765
0–2				1.939	1.31	0.562		0.112		1.348	1.23	0.618
0–3				1.175	1.24	0.523		0.257		0.853	1.17	0.578
0–4				0.979	1.33	0.530		0.289		0.698	1.20	0.615
0–1	E4	0.014	1.641	4.222	1.08	0.781	P4	0.001	0.064	1.507	1.26	0.770
0–2		0.017	1.064	3.499	1.22	0.621		0.001	0.064	1.367	1.22	0.626
0–3		0.003	0.922	1.342	1.25	0.528		0.002	0.163	0.871	1.16	0.591
0–4		0.005	0.483	0.677	1.26	0.577		0.004	0.106	0.702	1.11	0.676
0–1	E5	1.332		1.697	1.20	0.730	P5	0.309		0.729	1.13	0.729
0–2		0.898		0.804	1.25	0.601		0.359		0.529	1.12	0.663
0–3		0.804		0.551	1.28	0.493		0.391		0.544	1.14	0.601
0–4		0.719		0.472	1.31	0.546		0.368		0.543	1.21	0.614

[a]E is an exponential function and P is a power function, the form of which is given in Table 2

[b]RMSE is root-mean-square error

SOC as a function of depth and boundary SOC

Considering the large variation in SOC, particularly in the top soil (0–0.2 m), studies (Bernoux et al. 1998; Hilinski 2001) have ascertained the vertical distribution in SOC from those in the shallowest and deepest depths. Bernoux et al. (1998) and Hilinski (2001) expressed SOC as a function of depth using SOC at the shallowest and deepest depths in the soil profile. The results in using SOC at the shallowest and deepest depths to portray the vertical distribution in SOC (E3 and P3 in Table 2) are shown in Table 3 and Fig. 8. The power function resulted in a better fit to the data ($R^2=0.765$ and RMSE = 1.12 g kg^{-1} at a depth of 0–1 m) than the exponential function. The functions that predicted the vertical distribution in SOC from soil depth and SOC in the shallowest and deepest depths performed better than the functions that predicted SOC from soil depth and silt content (E2 and P2 in Table 3) or soil depth alone (E1 and P1 in Table 3).

SOC as a function of depth, texture, and boundary SOC

Storage of SOC in alluvial soils is dependent on several variables (Bullinger-Weber et al. 2014), such as profile development, texture, moisture, and water table depth (Mitra et al. 2005; Steiger et al. 2001). Therefore, functions were developed (E4 and P4 in Table 2) that relate the vertical distribution in SOC to soil depth, silt content, and SOC content at the shallowest and deepest depths in the soil profile. These variables, when included in an exponential and power function, provided good predictions of SOC with depth (Table 3 and Fig. 9). For example, in the upper 1 m of the soil profile, the exponential function had an R^2 of 0.781 and RMSE of 1.08 g kg^{-1} (E4 in Table 3). At deeper depths (0–3 and 0–4 m), the power function provided better estimates of SOC with depth (P4 in Table 3).

SOC as a function of depth and shallowest SOC

Although the addition of variables may improve the prediction of SOC with depth using mathematical functions, measuring soil properties is costly and time consuming (Christiaens and Feyen 2001; Jabro 1992), especially for deep soils. In addition, SOC content is easier to acquire near the surface than at deeper depths in the soil. Therefore, we developed simple functions that estimate the vertical distribution in SOC from SOC content at the shallowest depth and soil depth (E5 and P5 in Table 2). These functions provided good performance in predicting the vertical distribution in SOC based upon a relatively low RMSE and high R^2 (Table 3). The exponential (E5 in Table 3) and power (P5 in Table 3) functions performed well in the upper 1 m of the soil profile with an R^2 of 0.730 and 0.729 and

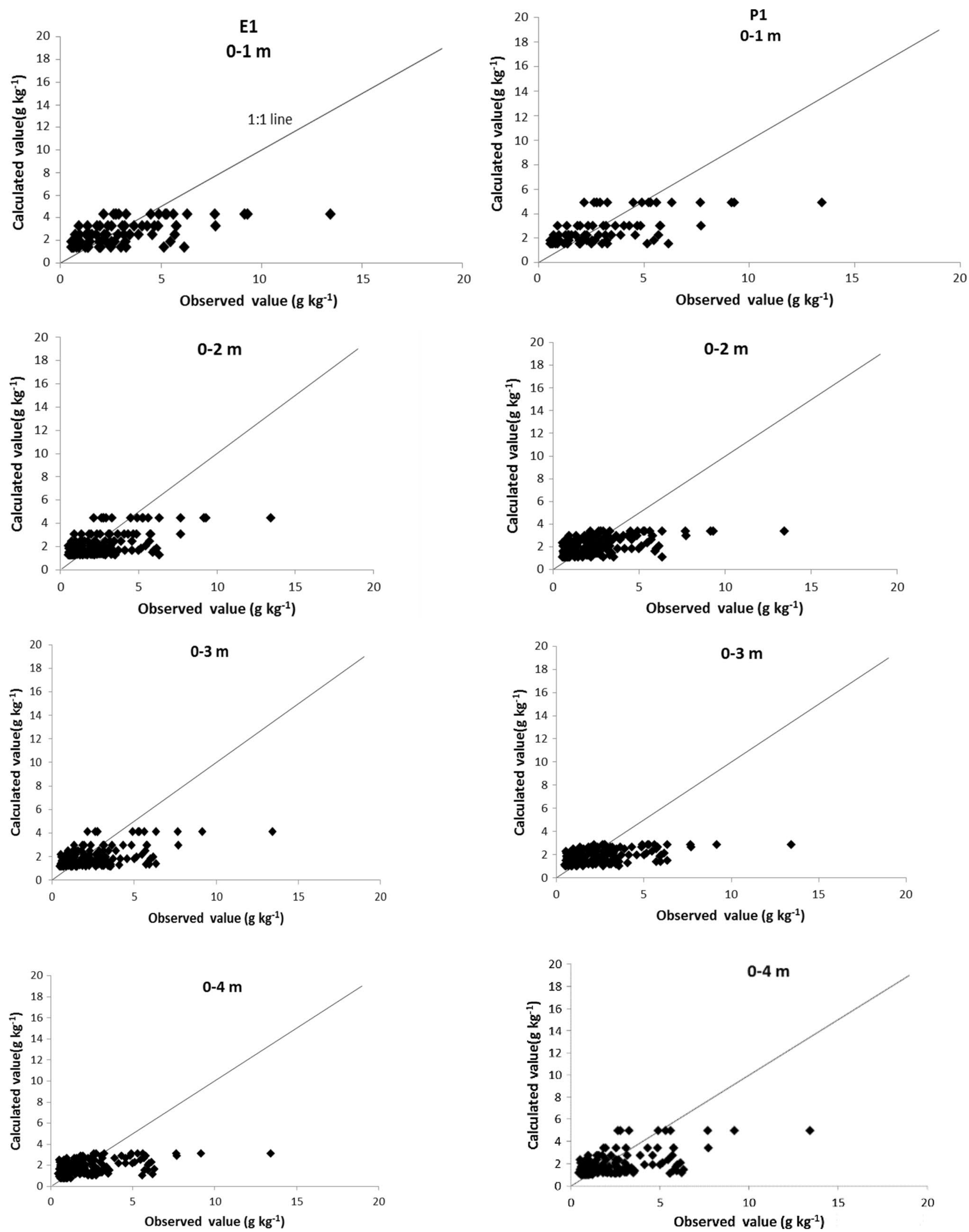

Fig. 6 Soil organic carbon (SOC) content as a function of soil depth. E1 and P1, respectively, refer to exponential and power functions in Table 2

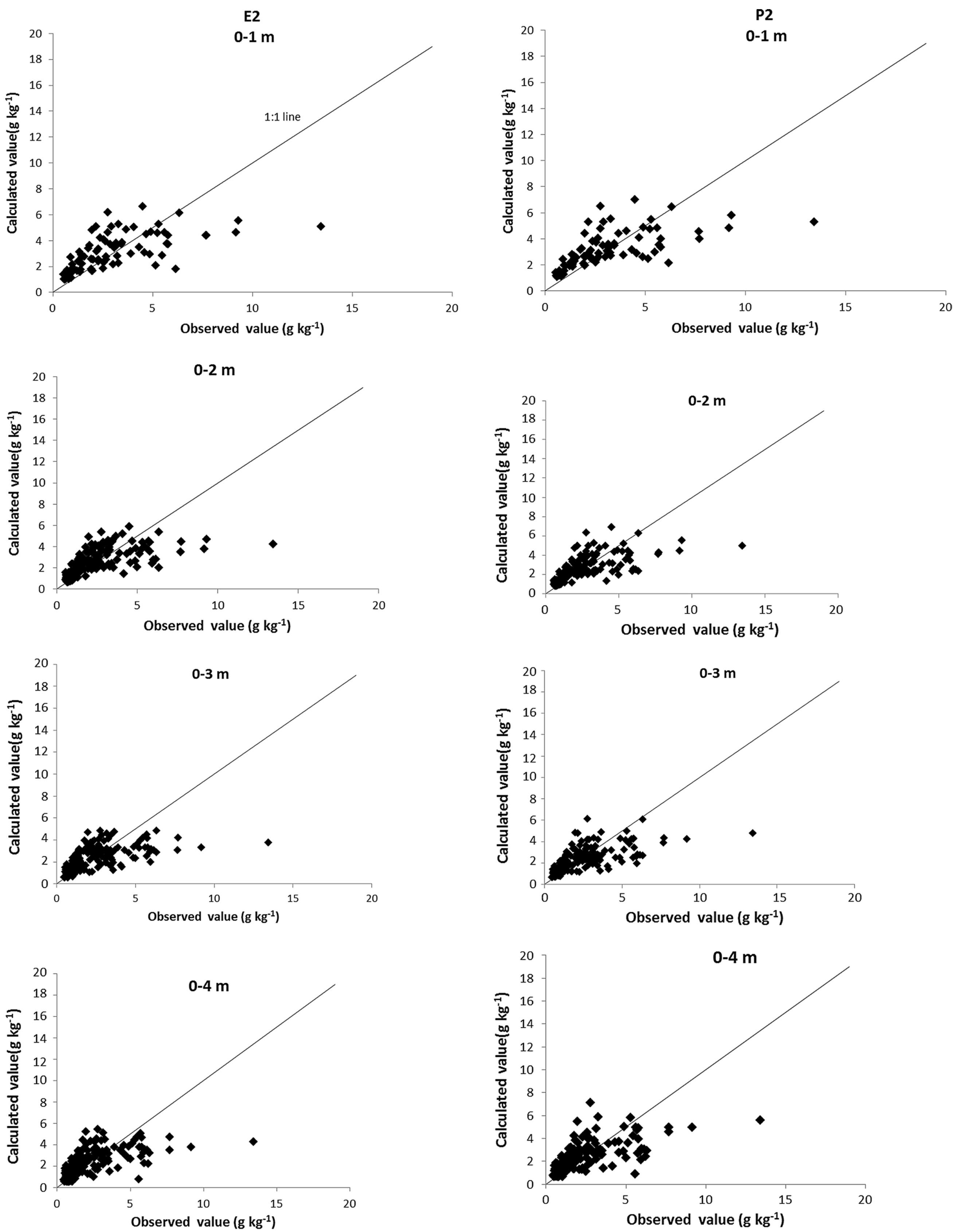

Fig. 7 Soil organic carbon (SOC) content as a function of soil depth and silt content. E2 and P2, respectively, refer to exponential and power functions in Table 2

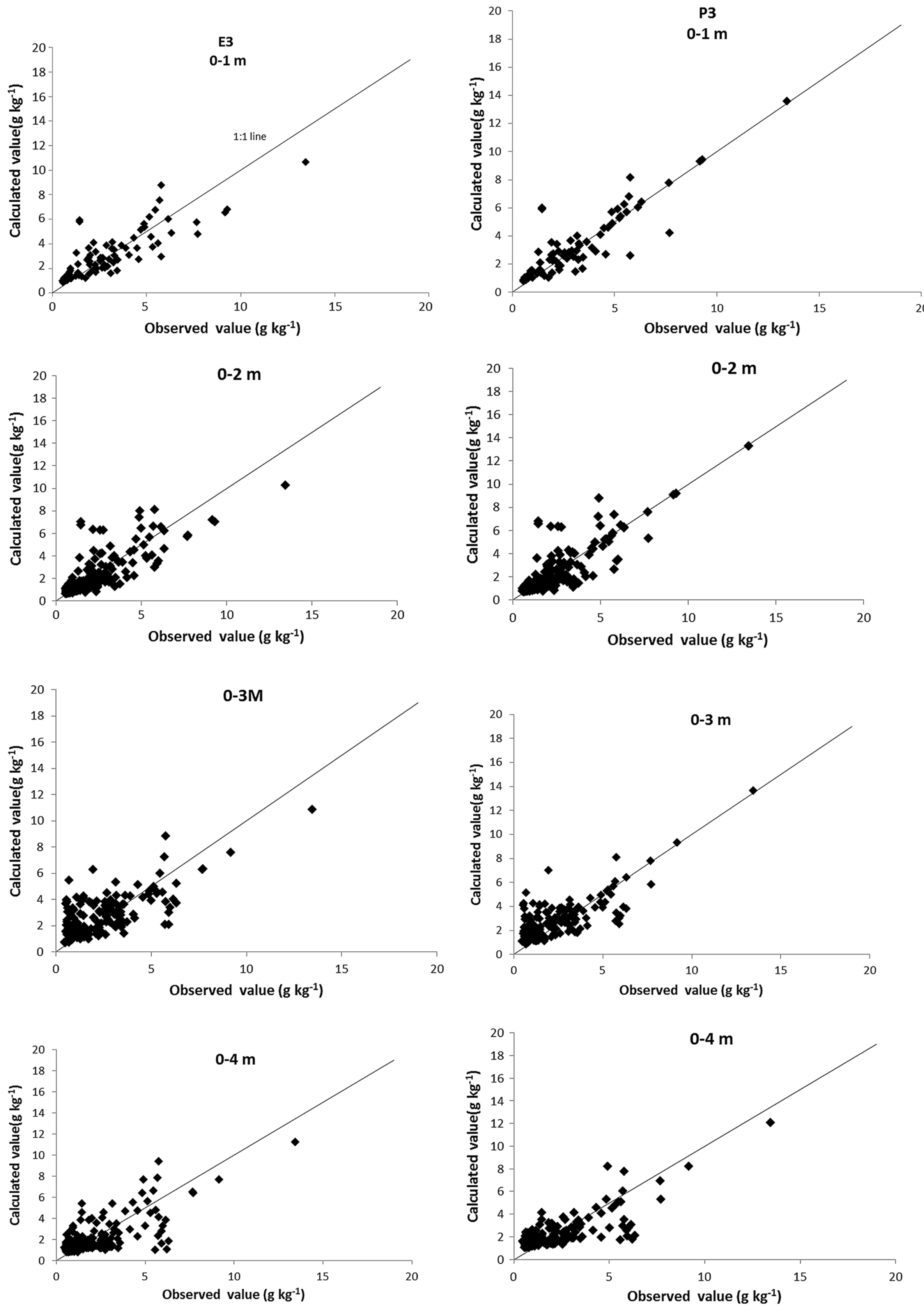

Fig. 8 Soil organic carbon (SOC) content as a function of soil depth and SOC at the shallowest and deepest depths. E3 and P3, respectively, refer to exponential and power functions in Table 2

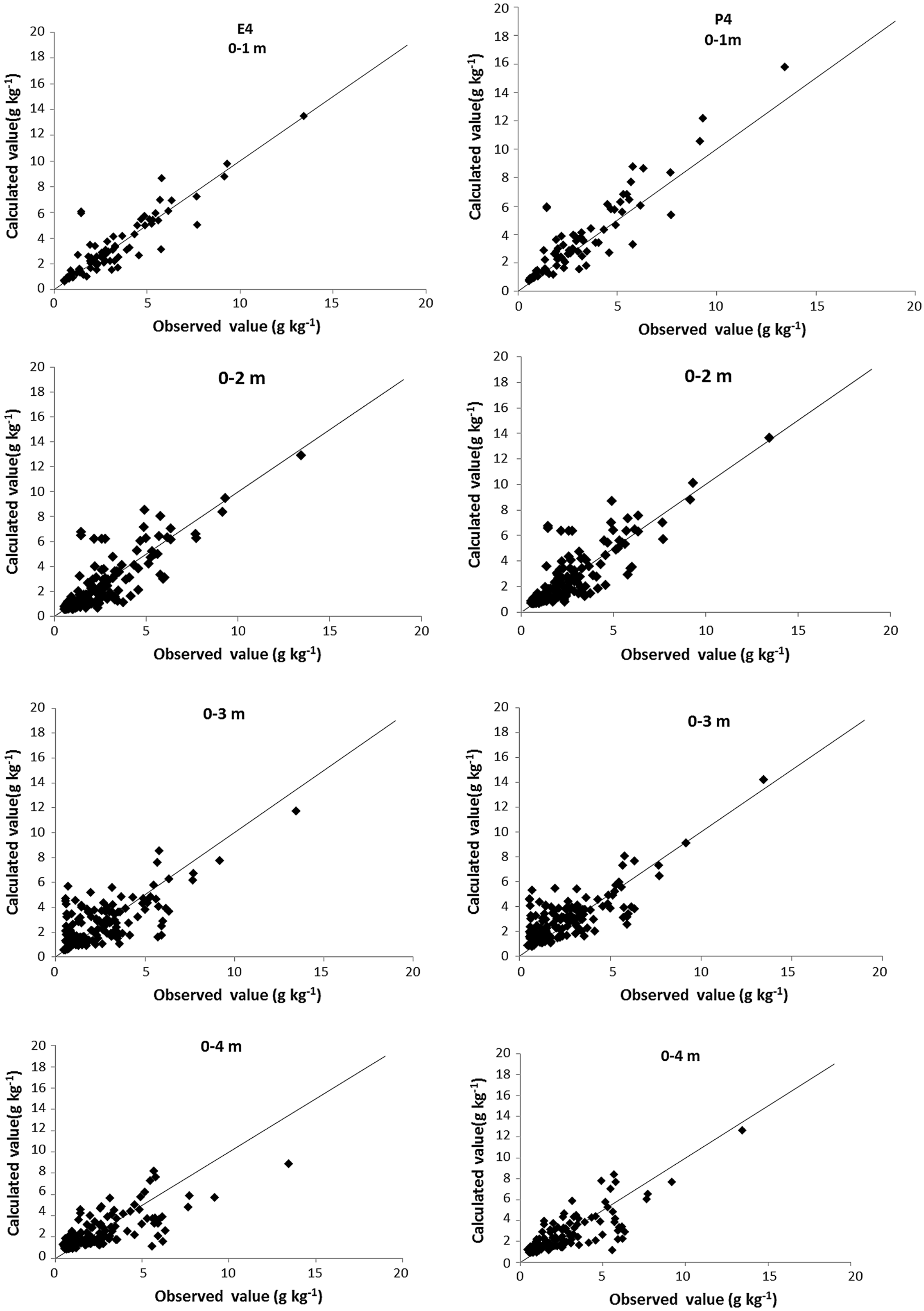

Fig. 9 Soil organic carbon (SOC) content as a function of soil depth, SOC at the shallowest and deepest depths, and silt content. E4 and P4, respectively, refer to exponential and power functions in Table 2

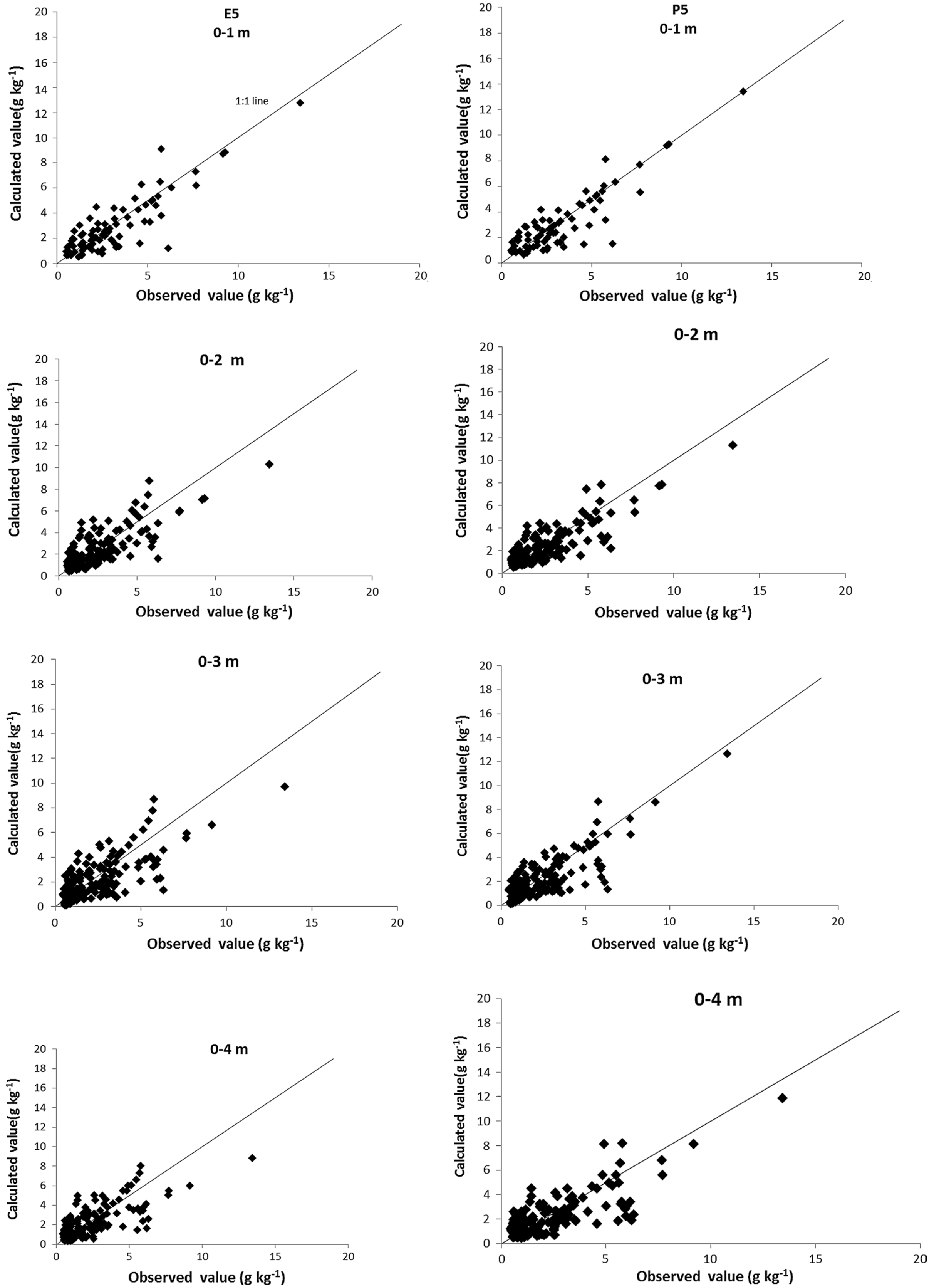

Fig. 10 Soil organic carbon (SOC) content as power and exponent functions of soil depth and SOC at the shallowest depth. E5 and P5, respectively, refer to exponential and power functions in Table 2

RMSE of 1.20 and 1.13 g kg^{-1}, respectively. However, the power function provided better performance in estimating SOC with depth at the 0–2, 0–3, and 0–4 m depths than the exponential function (Fig. 10). For example, the mean R^2 and RMSE over these depth intervals was, respectively, 0.626 and 1.16 g kg^{-1} for the power function and 0.547 and 1.28 g kg^{-1} for the exponential function.

Although SOC generally decreases with depth, Mishra et al. (2009) found that poorly drained soils have high subsoil SOC stocks. Therefore, exponential functions describing the relationship between SOC and depth may show poor performance in characterizing the depth distribution in SOC where subsoils are rich in SOC. Soils rich in SOC at depth generally have spodic and peat horizons (Aldana Jague et al. 2016; Ottoy et al. 2017; Sleutel et al. 2003). The soils at the five locations in our study had low clay content (Fig. 4) and were adequately drained. Li et al. (2016) reported good infiltration capability of soils in the Tarim River floodplain. Since SOC content decreased with depth, power and exponential functions were used to express the vertical variation in SOC in the floodplain.

The power function provided better prediction of the vertical distribution of SOC in a deeper soil profile than the exponential function. The main reason for the good prediction using the power function was the rapid decrease in SOC with soil depth (Fig. 3). Soil organic carbon content decreased more rapidly closer to the surface than at depth because SOC in the topsoil versus at depth is influenced more so by climate (Jobbagy and Jackson 2000), sediment deposition (Admiraal and Vanzanten 1988; Cuffney 1988), and wind erosion (Lal 2003; Lyles and Tatarko 1986). In contrast, SOC content changed little and appeared relatively stable at deeper depths, likely due to the slower cycling of SOC pools at depth (Paul et al. 1997; Trumbore 2000). Although dust may be generated from river sediments by the erosive forces of wind in floodplain of Tarim River (Li et al. 2013b), soils along the floodplain are also influenced by flooding.

Conclusions

Soil profiles were sampled and analyzed for SOC at five locations along the floodplain of the Tarim River. Our analyses indicate that SOC content ranged from 0.47 to 13.44 g kg^{-1} and had a mean value of 2.04 g kg^{-1} (SE of 0.10 g kg^{-1}), across all depths and locations. The top soil (0–0.2 m) had the highest SOC content, with a mean value of 6.28 g kg^{-1} (SE = 0.75 g kg^{-1}). Soil organic carbon content decreased sharply with depth, particularly in the upper soil profile. Power and exponential functions adequately described SOC as a function of depth within the upper 1 m of the profile, while the power function better described SOC as a function of depth for the 0–3 m and 0–4 m profiles. Furthermore, it was found that the vertical distribution in SOC content can be better predicted based upon SOC content at the shallowest depth and soil depth. Functions developed in this study that describe the vertical distribution of SOC may have limited application to other floodplain soils due to their empirical nature (Zinn et al. 2005). However, results from this study will enhance the understanding of SOC stocks in deep soil profiles.

Acknowledgements This research was supported by the National Natural Science Foundation of China (Grant No. 41571035) and Youth Innovation Promotion Association CAS (2017477).

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