

## Soil inorganic carbon stock under different soil types and land uses on the Loess Plateau region of China



Wen-Feng Tan<sup>a,b,\*</sup>, Rui Zhang<sup>a</sup>, Hua Cao<sup>a</sup>, Chuan-Qin Huang<sup>a</sup>, Qin-Ke Yang<sup>a</sup>,  
Ming-kuang Wang<sup>c</sup>, Luuk K. Koopal<sup>b,d</sup>

<sup>a</sup> State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, CAS and MWR, Yangling 712100, Shaanxi, China

<sup>b</sup> Key Laboratory of Arable Land Conservation (Middle and Lower Reaches of Yangtze River), Ministry of Agriculture, College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China

<sup>c</sup> Fujian Academy of Agricultural Sciences, Fuzhou 350003, Fujian, China

<sup>d</sup> Laboratory of Physical Chemistry and Colloid Science, Wageningen University, Dreijenplein 6, 6703 HB Wageningen, The Netherlands

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### ABSTRACT

The soil carbon reservoir is the largest carbon reservoir in terrestrial ecosystems and consists of soil organic and inorganic carbon stocks. Previous studies have mainly focused on the soil organic carbon (SOC) stock, and limited information is available about the soil inorganic carbon (SIC) stock. The Chinese Loess Plateau (CLP), which is located in the arid and semi-arid region of China, is an important inorganic carbon reservoir, with a thick soil layer that is rich in calcium carbonate. However, there are few reports on the SIC stock and its spatial distribution in this region. In the current study, the SIC densities and stocks for various soil types and land use patterns were evaluated based on 495 profiles with 2470 soil samples across the CLP, which were collected from the Chinese Second National Soil Survey. The results showed that in the top 1 m of soil across the CLP, the average SIC density is 17.04 kg/m<sup>2</sup>, and the total SIC stock is approximately 10.20 Pg C (1 Pg = 10<sup>15</sup> g). The SIC stock of the CLP accounts for approximately 18.4% of the total SIC stock throughout China. The average values of the SIC stock in the 0–20, 20–50 and 50–100 cm depths of the CLP are 2.39, 2.92 and 4.89 Pg, respectively. Under different land use patterns, the order of the average SIC density is farmland ≈ grassland > forest in all soil layers. For the various soil types, the SIC density in the 0–100 cm layer is the highest in alkaline soil and lowest in subalpine meadow soil, whereas the SIC stock is highest in loessial soil, eolian sandy soil and sierozem, and the lowest in subalpine meadow soil. These differences are largely a result of the area occupied by each soil type and the climate conditions. The results of this study provide basic information about carbon reservoir in China and contribute to our understanding of the SIC stock on the CLP as it relates to the carbon balance of terrestrial ecosystems.

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### 1. Introduction

As an important part of the global carbon cycle, the terrestrial carbon ecosystem affects not only the global carbon balance but also the global temperature change (Eswaran et al., 1993). Soils have the potential to mitigate atmospheric CO<sub>2</sub> concentrations through C sequestration with a maximum global potential estimate ranging from 0.45 to 0.9 Pg C (1 Pg = 10<sup>15</sup> g) per year (Lal, 2004). The soil carbon reservoir consists of soil organic carbon (SOC) and soil inorganic carbon (SIC). Most attention has been given to SOC, mainly because for most regions SOC contributes more to the carbon content than SIC and SOC affects the soil adsorption of CO<sub>2</sub> and the soil density distribution (Fang et al.,

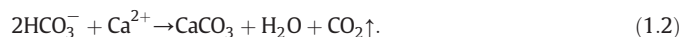
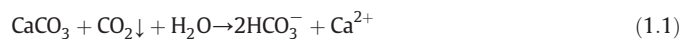
2001; Li et al., 2007, 2013; Liu et al., 2006, 2011; Wang and Zhou, 1999; Wang et al., 2012; Wu et al., 2003; Yu et al., 2007a, 2007b). However, in arid and semi-arid areas, which cover one third of the earth's surface, SIC is the dominant form of carbon (Lal and Kimble, 2000; Mi et al., 2008; Mielnick et al., 2005), and in these areas the SIC reservoir is approximately 2–10 times larger than that of SOC (Eswaran et al., 2000; Schlesinger, 1982).

The SIC reservoir consists mainly of carbonates (Schlesinger, 2002) and most research has been conducted on SIC in the form of carbonate (Li et al., 2007; Mi et al., 2008; Pan, 1999; Wu et al., 2009). SIC is divided into primary carbonate and secondary deposited carbonate (Ming, 2002). Primary carbonates are inherited from parent material of the soil. Secondary carbonates are formed through the dissolution and precipitation of carbonate parent material and derived from the weathering of calcium silicate. In the dissolution and precipitation of carbonate atmospheric CO<sub>2</sub> can be involved through a series of chemical reactions (Feng et al., 2001; Scharpenseel et al., 2000; Yang et al., 2010).

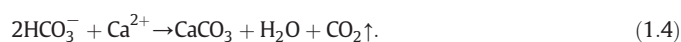
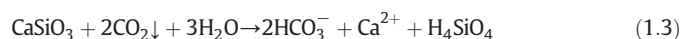
\* Corresponding author at: Key Laboratory of Arable Land Conservation (Middle and Lower Reaches of Yangtze River), Ministry of Agriculture, College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China.

E-mail address: [wenfeng.tan@hotmail.com](mailto:wenfeng.tan@hotmail.com) (W.-F. Tan).

In principal, one unit of CO<sub>2</sub> is consumed when one unit of carbonate is dissolved (Eq. (1.1)), and an equal amount of CO<sub>2</sub> is released when carbonate is re-deposited (Eq. (1.2)) (Wu et al., 2009):



Therefore, dissolution and precipitation of secondary carbonate balance each other with respect to atmospheric CO<sub>2</sub>. The formation of secondary carbonate from calcium silicate also involves CO<sub>2</sub> (Emmerich, 2003; Goddard et al., 2007; Lal and Kimble, 2000; Wu et al., 2009). Atmospheric CO<sub>2</sub> can be fixed or released through, respectively, calcium silicate dissolution (Eq. (1.3)) and secondary carbonate deposition (Eq. (1.4)):



Hence, weathering of a calcareous layer consumes 2 units of CO<sub>2</sub>, but only 1 unit of CO<sub>2</sub> is released in the deposition of secondary carbonate. This can lead to the sequestration of atmospheric CO<sub>2</sub> in soils (Adams, 1993; Lal and Kimble, 2000; Wu et al., 2009). Next to the role of carbonate in fixation and release, it is also well known that the free form of carbonate affects soil oligomers, soil microbial activity, soil pH and the decomposition rate of soil organic matter. Furthermore, the SIC reservoir can be influenced by potential soil acidification through climate changes, for instance, the continuous acid deposition and agricultural activities. Such soil acidification can lead to large C losses from soil carbonates (Bowman et al., 2008; Entry et al., 2004; Mikhailova and Post, 2006; Papiernik et al., 2007; Sartori et al., 2007; Weng, 1995). Following Emmerich (2003), Singh et al. (2007) and Wu et al. (2001), it can thus be concluded that the SIC reservoir and its distribution play an important role in the dynamic changes of the atmosphere, the vegetation and the soil. Therefore, an accurate estimate of the SIC contribution to the soil carbon reservoir is required for a correct appreciation of the role of soils in the global ecosystem.

The Chinese Loess Plateau (CLP), located in the arid and semi-arid climate, covers a large area and, as such, is consequential to the global carbon cycles (Wang et al., 2011; Wen, 1989). Although investigations in China have been conducted on SIC on a national scale (Mi et al., 2008; Pan, 1999; Wu et al., 2009) and regional scale (Feng et al., 2001; Wang et al., 2013; Xu et al., 2009; Yang et al., 2010), the distribution of SIC on the integral CLP is largely unknown. Therefore, the aim of the present paper is to obtain more insight in the SIC reservoir of the CLP, which in turn will lead to a better understanding of the importance of the CLP for the global carbon cycles. The objectives of this study were (I) to estimate the SIC stock and SIC density in the 1 m soil horizon based on mainly 495 profiles with 2470 soil samples across the CLP collected from the Chinese Second National Soil Survey, and (II) to discuss the major factors that influence the SIC density and stock under different land uses, soil types and soil layers.

## 2. Materials and methods

### 2.1. Study area and data sources

The Chinese Loess Plateau (CLP) is located in the northwest of China (Fig. 1), which includes the upper and middle courses of the Yellow River (Shi and Shao, 2000). The plateau is surrounded by the Taihang mountain range to the east, Riyue-Helan Mountain to the west, the Qinglin range to the south and the Yinshan Mountain to the north (N33°43′–41°16′, E100°54′–114°33′). The CLP covers a total area of

620,000 km<sup>2</sup>, with elevations ranging from 200 to 3000 m. The region is dominated by a temperate of arid and semi-arid continental monsoon climate. The mean annual temperature ranges from 3.6 to 14.3 °C, while the mean annual precipitation ranges from 150 to 800 mm. The precipitation occurs mainly between June and September, and decreases along a southeast to northwest transect (Yang and Shao, 2000). The vegetation zones occur in the following sequence: forest → forest-steppe → typical-steppe → desert-steppe → steppe-desert (Wang et al., 2010).

In this study, the soil data came mainly from the Second National Soil Survey in China, including Soil Species of China (NSSO, 1995a, 1995b, 1998) and the provincial soil survey (HNSSO, 2004; IMARSSO, 1994; Liu and Zhang, 1992; QARRPO, 1995). From the Second National Soil Survey 495 soil profiles (see Fig. 1 for the locations) were used. In total 2470 soil samples were collected over the soil horizons to analyze. Information in the database on the soil profiles include mostly profile depth, horizon thickness, organic matter content, calcium carbonate content, gravel content (particle diameter larger than 2 mm) and soil bulk density of the different horizons. These properties were determined by conventional methods (NSSO, 1998; Wu et al., 2009). Soil calcium carbonate was determined using the Chittick apparatus (Dreimanis, 1962). Soil organic carbon contents were determined by the potassium dichromate wet oxidation method (Walkley and Black, 1934). Soil bulk density was determined by the cutting ring method (Black and Hartge, 1986) and gravel content was measured using a 2-mm sieve. The data of the other surveys contained similar information.

The areas of each soil type were identified using the 1:500,000 Soil Map of the Chinese Loess Plateau, which is supplied by the Institute of Soil and Water Conservation, Chinese Academy of Sciences (CAS).

### 2.2. Data analysis

#### 2.2.1. Calculation of the soil inorganic carbon content

To allow comparison with other studies, the calculation of the SIC stock in the present study is based on the soil profile data in the horizon of 0–100 cm. To obtain detailed information the soil profiles were subdivided into three standard horizons of 0–20 cm, 20–50 cm and 50–100 cm. In the soil survey data, the stratification of the soil profiles was often based on the characteristic soil horizons, and these did not necessarily coincide with the depth-based layers in the present study. Therefore, data of the pedogenetic horizons (i.e., O, A, B, C) were converted to depth-based layers. The calculation was based on the actual data for the different soil horizons. When the actual soil depth was deeper than 100 cm, only the CaCO<sub>3</sub> contents in the 0–100 cm horizons were used. When the actual depth of soil profiles in the soil survey data was less than 100 cm, the CaCO<sub>3</sub> content of the layer beneath the actual depth of the soil profile up to 100 cm was regarded as zero. During converting from pedogenetic horizons to three depth layers (0–20, 20–50, 50–100 cm), the depth of each horizon was used as a weighting coefficient according to their relative contributions to the overall depth, so as to derive the average CaCO<sub>3</sub> content of the soil profile to a depth of 20, 50 and 100 cm. For each soil profile the weighted CaCO<sub>3</sub> content by depth zone were calculated as product of depth of horizon, concentration of CaCO<sub>3</sub> and bulk density (Mi et al., 2008; Palmer et al., 2002). For example, to estimate inorganic carbon content in the 0–20 cm layer soil, the depth of the O horizon was used as the criterion to assign characteristics. When the thickness of O horizon was >20 cm, a layer of 20 cm was assumed with its characteristics equal to that of the O horizon. When the thickness of O horizon was <20 cm, an additional part from A horizon was taken with its properties to make up the 20 cm and average properties of the 0–20 cm layer were calculated from the weighted properties of the O horizon and the A horizon, weighting the amounts according to their relative contributions to the overall depth.

#### 2.2.2. Calculation of soil bulk densities

In some cases soil density data were missing in the national soil survey but the soil organic carbon content (SOC) was known. In this case

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