Soil & Tillage Research 163 (2016) 274–281

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Distribution of soil carbon and grain yield of spring wheat under a permanent raised bed planting system in an arid area of northwest China

Zhongming Ma[a,*], Juan Chen[b,c], Xiaodong Lyu[a], Li-li Liu[d], Kadambot H.M. Siddique[e]

[a] Gansu Academy of Agricultural Sciences, Lanzhou, Gansu 730070, PR China
[b] College of Agriculture, Gansu Agricultural University, Lanzhou, Gansu 730070, PR China
[c] Qingyang Academy of Agricultural Sciences, Qingyang, Gansu 745000, PR China
[d] Zhuoni Bureau of Meteorology, Zhuoni County, Gannan Tibetan Autonomous Prefecture, Gansu 747600, PR China
[e] The UWA Institute of Agriculture, The University of Western Australia, M082, LB 5005, Perth, WA 6001, Australia

ARTICLE INFO

Article history:
Received 6 December 2015
Received in revised form 30 April 2016
Accepted 13 May 2016
Available online 18 July 2016

Keywords:
Permanent raised bed
Soil total carbon
Particulate organic carbon
Soil microbial biomass carbon
Carbon stratification ratio

ABSTRACT

Soil organic carbon (SOC) plays a crucial role in improving soil properties and the C global cycle. Judicious tillage management can improve soil fertility and quality, and effectively reduce greenhouse gas emissions by enhancing soil carbon sequestration. An 8-year (2005–2012) field experiment was conducted in arid northwestern China to evaluate the effect of tillage practices on the distribution of total organic carbon (TOC), particulate organic carbon (POC) and microbial biomass carbon (SMBC) at 0–5, 5–10, 10–20, 20–40, 40–60 and 60–90 cm soil depths, as well as TOC stratification, TOC stocks and grain yield of spring wheat (*Triticum aestivum* L.). Spring wheat was grown under three tillage systems: (1) permanent raised beds–zero tillage and ride culture with controlled traffic (PRB), (2) no-tillage planting on a flat field with controlled traffic (FB) and (3) traditional tillage –conventional tillage without residue retention (TT). A tillage effect was observed on TOC, POC and SMBC, which was significantly higher in the surface soil layer (0–10 cm) in permanent raised beds (PRB) than in TT and FB. No differences in TOC or POC were encountered at 10–20, 20–40 and 60–90 cm between treatments. Below 10 cm, no differences in SMBC were observed between treatments, but TOC and POC contents at 40–60 cm were significantly higher under TT than FB, with TT > PRB > FB. PRB had the highest TOC storage in the 0–90 cm soil profile (75 Mg C ha^{-1}) followed by FB (74 Mg C ha^{-1}) and TT (69 Mg C ha^{-1}). Higher TOC stratification was observed under PRB and FB than under TT. Six years of PRB increased mean grain yield by 6% and 9% compared with TT and FB, respectively. We conclude that: (1) conservation tillage with controlled traffic (PRB and FB) increased TOC, POC and SMBC concentrations (0–10 cm) and TOC stock, (2) SMBC is a sensitive indicator for reflecting the effect of agricultural management practices on TOC dynamics, and (3) PRB tillage could sustain wheat grain yields and increase carbon sequestration in arid northwestern China, such that PRB tillage is a more sustainable wheat cropping system than the TT system currently used by most farmers.

1. Introduction

Wheat is the most important crop in the annual production systems of northwest China, especially in the He-Xi Corridor (38°85′N, 100°81′E) of Gansu Province. Farmers face the challenge of developing sustainable agricultural practices to improve poor wheat yields. Water shortage (annual average rainfall is <150 mm) and low soil quality lead to low yields. Wheat farming in this area is dependent on irrigation. Traditional tillage with frequent, intensive operations (generally involving numerous tillage trips which disturb the soil surface and are performed prior to, during planting or after harvest) and flood irrigation adopted by most farmers leaves the soil bare after harvest and prior to planting the next crop. Repeated plowing alters the soil structure by exposing more soil organic matter (SOM) to microbial transformation, and influences the physical, chemical and biological properties of the soil, which ultimately affects the formation and stabilization of macroaggregates. Failure to protect and maintain SOM leads to

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[*] Corresponding author.
E-mail address: mazhming@163.com (Z. Ma).

http://dx.doi.org/10.1016/j.still.2016.05.010

water and wind erosion, water evaporation and soil quality deterioration, with subsequent poor production and low water and nutrient use efficiencies (Saha and Ghosh 2013; Elcio et al., 2003; Huang et al., 2007). Unacceptable soil compaction generally occurs when harvesting wheat in Zhang-ye city as the probability of rainfall is high during harvest (end of July) and the level of mechanization is low (existing tractors are less than 20 hp and many only have single axles) (Ma et al., 2005). On a wet soil, single axle tractors (a small tractor carried on a pair of wheels fixed to a single-drive while the operator usually walks behind gripping a pair of handles) can compact the soil severely causing low wheat and rice grain yields (Raper et al., 2000). The use of permanent raised beds (PRB) as a new conservation management technique, with its essential features of ridge tillage, controlled traffic (all heavy equipment wheels are confined to controlled traffic lanes) and furrow irrigation. PRB was adopted in the He-Xi Corridor of 2005 to minimize soil degradation, save water and increase water and nutrient availability to crops. Residues are left on the soil surface and soil disturbance is limited to reshaping the beds for the next cropping season. Compared with traditional tillage systems, the benefits of PRB include soil protection from water and wind erosion (Hakim and Helena 2010), more effective control of irrigation water and drainage, reduced evaporation and crop lodging (Bakker et al., 2010), improved nutrient (N, P and K) use efficiency (Ma'shum et al., 2009), increased crop yields and reduced management expenses (Choudhury et al., 2007; Zahid et al., 2010).

Soil carbon is strongly related to soil fertility and crop productivity. There is a strong link between soil fertility and soil organic carbon (SOC) density and storage (Min et al., 2013). No-tillage farming management practices improve SOC sequestration and, in turn, reduce soil CO_2, CH_4 and N_2O emissions which improve the health of cropping soil systems while reducing greenhouse gas emissions that might otherwise contribute to global climate change (Sun et al., 2011). Soil microbial biomass and SOC content tend to increase under conservation tillage compared to conventional tillage. As much as 60% of SOC in temperate regions and 75% in the tropics are depleted by conventional moldboard plowing (intensive tillage systems), contributing recently to about 20% increases in atmospheric CO_2 concentration (Lal 2004). To halt and possibly reverse the reduction of SOC, conservation tillage, particularly no-till systems, are being promoted to improve soil health (Nie et al., 2016), but some authors have argued, however, that incorporating crop residues into the soil in conventional systems would result in increasing SOC in deeper soil layers, tillage regime just influence the distribution of soil carbon, so deeper samplings are needed to detect differences between tillage systems (Baker et al., 2007; Govaerts et al., 2009).

However, changes in SOC occur over long periods of time, so improvements in soil health have to be sensitive to small changes produced over the short time of most tillage experiments (Gregorich et al., 1998; Smith et al., 2005). Soil microbial biomass C (SMBC) and particulate organic C (POC) are among the biologically-labile C fractions that respond more rapidly to soil management and land use changes than total SOC (Gosling et al., 2013). POC is the fraction that is preferentially lost when soil is conventionally cultivated for long periods of time (Cambardella and Elliott 1992; Chan 2001). Conversely, POC is the fraction gained when conservation tillage is employed. Soil microbial biomass C is a biological indicator of soil fertility that accounts for only 1–3% of SOC and is the 'eye of the needle' through which all organic material that enters the soil must pass (Jenkinson 1977). In agricultural soils, 200–1000 mg SMBC g^{-1} can fix 100–600 kg N ha^{-1} in tilled layers (Martens 1995).

The stratification ratio (SR) of SOC (concentration of SOC in the surface divided by that deeper in the soil profile) can be used as an indicator of soil health under different tillage treatments, the surface is topsoil, which is strongly influenced by quality of soil management (tillage and cropping system), and the deeper soil layer is a subsoil layer, which is less affected by these farming operations (Franzluebbers 2002; Chan et al., 2002). In general, whatever the soil and climatic conditions are, a high SR would indicate good soil quality as SRs >2 are not frequently found in degraded soils (Lo′pez-Fando and Pardo, 2011).

Few experiments have been conducted to determine the influence of PRB tillage on soil carbon over the whole 0–90 cm soil depth range in the arid northwest of China. Hence, the objective of this study was (1) to evaluate the effects of PRB, zero tillage planting on a flat field with controlled traffic (FB) and traditional tillage (TT) on the grain yield of spring wheat over eight years of adopting the new system; (2) to assess soil carbon contents (TOC, POC and SMBC) under PRB, FB and TT; and (3) to evaluate the effects of PRB, FB and TT on stratification of SOC in arid northwest China.

2. Materials and methods

2.1. Site description

In 2005, a field experiment was initiated at the GAAS (Gansu Academy of Agricultural Sciences) Water-saving Research Station (38°85′N, 100°81′E) located 1555 m above sea level at Zhang-ye in the He-Xi Corridor of northwest China. The basic soil properties at the experimental site are presented in Table 1. A spring wheat (*Triticum aestivum* L.) and spring maize (*Zea mays* L.) rotation (one crop per year) is commonly planted in this area. During the course of this experiment, maize was planted in 2008 and 2011. As there were no differences with respect to maize grain yield among treatments (date not shown), only measurements recorded in the years sown to spring wheat (2005, 2006, 2007, 2009, 2010, 2012) are presented in this paper. Spring wheat is usually planted at the end of March and harvested at the end of July. The area has a typical arid climate and the soil type is an Aridisol (sierozem). Annual mean temperature is 7.39 °C, cumulative temperatures above 0 and 10 °C are 3394 and 2897 °C, respectively. The frost-free period is 150–160 days. Total solar radiation is 5988 MJ m^{-2} $year^{-1}$. Potential pan-evaporation is 2390 mm, average annual rainfall is 147 mm with uneven and low rainfall events—70% of the rainfall occurs during the monsoon season (June to September). During the wheat-growing season of 2012, total precipitation was 119 mm, maximum mean air temperature was 24.3 °C and minimum mean air temperature was 8.61 °C, as recorded by the Zhang-ye City Meteorological Bureau (Fig. 1).

Table 1
The basic physical and chemical properties of the soil (0–20 cm) in 2005 at the experimental site.

pH	Total nitrogen (g kg^{-1})	Organic matter (g kg^{-1})	Avail. phosphorus (mg kg^{-1})	Avail. potassium (mg kg^{-1})	Bulk density (Mg m^{-3})	Na^+ (g kg^{-1})	K^+ (g kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Soil type
8.58	0.78	12.49	13.72	223.7	1.38	5.07	0.76	490	340	170	Sandy loam