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Soil loosening on permanent raised-beds in arid northwest China

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Abstract

Poor lateral water infiltration into permanently raised beds (PRB) can reduce crop yield and water use efficiency (WUE) in dryland agriculture. Especially for densely planted crops the reduced soil moisture affects seedling emergence and causes slow crop growth. Soil loosening with three different types of cutters was tested to overcome this problem of wide PRB in this study. A field experiment with five treatments (traditional tillage, bed without soil loosening, bed with soil loosening by two-edge cutter, bed with soil loosening by flat cutter and bed with soil loosening by V-shaped cutter) was conducted in the Hexi Corridor, northwest China, on spring wheat in 2005 and 2006. The effects of soil loosening and the performances of the three cutters were assessed based on 2 years of soil moisture, bulk density, temperature, spring wheat growth, yield, WUE, power and fuel consumption data. Soil loosening significantly increased lateral water infiltration and thus improved soil water content by 3–8% to 100 cm depth and soil temperature by 0.2–0.4 °C to 30 cm depth compared to beds without soil loosening on sandy-loam soil in 100 cm wide bed systems. Furthermore, bulk density at 10–20 cm depth was about 7.4% lower for bed with soil loosening treatments than for bed without soil loosening. The best results were achieved by the V-shaped cutter, which at a slight additional fuel consumption of 0.46–0.84 l ha^{-1} offered the greatest benefits to spring wheat yield and WUE. Spring wheat yields increased by 5% and WUE improved by 38% compared to traditional tillage due to higher soil moisture and temperature, lower bulk density and faster growth. The improvements in WUE have tremendous implications in the arid areas of northwest China where agriculture relies heavily on irrigation, but water resources are scarce. We conclude therefore that soil loosening by V-shaped cutter is an efficient way to remove poor water infiltration, and significantly improve yield and WUE for wide beds under PRB farming system in arid areas of northwest China.

Keywords: Permanent raised-beds; Soil loosening; Water infiltration; Water use efficiency; Spring wheat; Arid areas

1. Introduction

Agriculture in the arid Hexi Corridor of northwest China, where rainfall is less than 200 mm per year, relies heavily on irrigation. Maintaining or improving water use efficiency is extremely important because the limited water resources available for irrigation mainly come from a mountain glacier (Kang et al., 1996). Many water-saving techniques have been tested to ensure the sustainable development of agriculture. Furrow irrigation of permanent raised-beds (PRB) has been adopted widely in arid areas of northwest China. Compared with the traditional flat till, flood irrigation farming systems, PRB is a contemporary farming practice involving bed planting, furrow irrigation, and controlled traffic. PRB requires keeping the beds and furrows permanently in the same position and only repairing the bed every year before the next crop is planted (Sayre and Moreno, 1997; Singh, 2003). Permanent raised-beds are effective in increasing water use efficiency (WUE) (Wang et al., 1999, 2002), reducing compaction of the cropping zone,

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and managing crop residues on the bed (Talukder et al., 2002). PRB has been shown to improve mechanical and chemical weed control, facilitate zero-tillage, and reduce tractor power requirements (Ren et al., 2001; Timsina and Connor, 2001; Hulugalle and Daniells, 2005).

Recent research results have promoted the development and extension of PRB farming system all over the world. Francois et al. (1999) developed a new cropping system to manage water under PRB in Thailand for an Asian rice-based system. Hobbs et al. (2000), Humphreys et al. (2004) and Kukal et al. (2005) systematically researched PRB farming systems in the rice–wheat systems of the Indo-Gangetic plains of southern Asia, while Ockerby and Fukai (2001) studied the management of rice grown on raised beds with continuous furrow irrigation in northern Queensland, Australia. In more arid environments, Wang et al. (2004a) compared PRB and traditional tillage for winter wheat from 1998 to 2002 in northern China.

Wheat (including both spring and winter habit wheat) is the most popular cereal crop in northwest China, especially in Hexi Corridor. In PRB farming systems, 100 cm wide beds systems for wheat planting are the most common because of the dimensions of tractor and harvester wheel spacing. Furthermore, in the same field, wide beds decrease traffic lanes in comparison with narrow beds, which enhances cropping zones and land use efficiency.

A major problem in wide beds is that irrigation water is difficult to laterally infiltrate from the furrow to the center of the bed, where crop water requirements are therefore often not met. Zhang et al. (2005) tested water infiltration on sandy-loam soil in 1.0 m wide bed planting system with furrow irrigation. The results showed that with 90 mm of irrigation water, wetting front required about 290 min to horizontally infiltrate from furrow to the center of bed, while it already reached near 100 cm depth under the furrow in vertical, so only less than 20% of irrigation water was stored in the center of bed. Poor lateral water infiltration in wide beds can therefore adversely affect crop germination, growth and yield. Wang et al. (2004b) reported that on loamy soils non-uniform lateral infiltration into beds wider than 75 cm reduced plant available water in the center of the beds. The lack of water in the center had a negative effect on winter wheat seedling emergence, lowering yield by 5% and decreasing water use efficiency by 6% compared to beds with less than 75 cm furrow-to-furrow distance. In the Hexi Corridor, Wu (2006) demonstrated that yield and center row yield of spring wheat in 70 cm wide beds (three rows) was about 10 and 23% higher than in 100 cm wide beds (five rows), respectively. Deng et al. (2005) and Ma and Wang (2005) also found that narrow bed planting systems had the advantages of higher water content and spring wheat yield in center rows compared to 100 cm bed planting system. The more uniform distribution of irrigation water in beds ranging from 70 to 90 cm width also provides more flexibility for gravity irrigation, efficient management of fertilizer, and easier handling of high levels of crop residues (Sayre et al., 2005).

The irrigation problems of wide beds in PRB farming systems have been known for some time, but few studies on ways to remove poor lateral water infiltration have been conducted. In this paper, the results of a project funded by the Australian Centre for International Agricultural Research (ACIAR) on the use of soil loosening to facilitate water penetration from the furrow to the center of the bed are reported. A soil loosening cultivator, equipped with three kinds of bed cutters designed to open a layer with macro-pores at the bottom of the bed, was tested. The aim of the study was to identify whether soil loosening improves uniform water infiltration into the bed, and if there was a positive effect on yields and water use efficiency in the Hexi Corridor of northwest China. The study also assessed which shape of cutter is most suitable cutter for soil loosening.

2. Materials and methods

2.1. Site and climatic conditions

The experiment was conducted at GAAS (Gansu Academy of Agricultural Science) water-saving research station (latitude 38°50′N, longitude 100°10′E), Zhangye city situated in the Hexi Corridor of northwest China, for two crop cycles in 2005 and 2006. Zhangye is located in warm–temperate arid region at 1200–1700 m above sea level. According to the statistics of Zhangye Weather Station, the normal annual precipitation is 146 mm. Mean annual pan-evaporation is around 2390 mm, 16 times greater than annual precipitation. The annual mean air temperature is about 7.3 °C, with an absolute maximum of 39.1 °C (July) and an absolute minimum of 27 °C (January). Accumulated temperature of ≥10 °C is about 3088 °C during an average of 169 frost-free days per year. The single crop cycle consists of spring wheat, sown in March and harvested in July, and irrigated in middle of April, May and June, respectively. In the experimental plots the soil was a sandy-loam, low in organic matter and slightly alkaline (Table 1).

Table 1
Soil characteristics of the experimental field at 0–20 cm depth

Texture (%)	
Sand	51
Silt	33
Clay	16
Soil organic matter (%)	0.92
pH	7.9

2.2. Experimental design

The experiment tested a soil loosening cultivator with three kinds of cutters: a two-edge cutter, a flat cutter and a V-shaped cutter, designed by China Agricultural University in 2004 (Fig. 1). The soil loosener consists of a toolbar frame, a fastener and the cutter blade itself. The toolbar frame was designed into multipurpose structure, so different cutters could be installed according to the requirement. The two-edge cutter just loosens the two sides of the bed's bottom. The blade of the flat cutter with the double-wing shape loosens the whole bottom of the bed. The blades of two-edge and flat cutter are just 5 mm thick, which can facilitate the cutters entering into the soil and reduce operational resistance. The V-shaped cutter is downward pointing, which improves the soils permeability by loosening the bed to a depth of 15–20 cm below the base of the furrow. Loosening below the level of the furrow bottom enhances the effect of gravity on infiltration of irrigation water from furrows into beds.

Five tillage treatments in a single spring wheat cycle system were compared: traditional tillage (TT), bed without soil loosening (NL), bed with soil loosening by two-edge cutter (TC), bed with soil loosening by flat cutter (FC) and bed with soil loosening by the V-shaped cutter (VC). Traditional tillage included moldboard ploughing, followed by tillage for seedbed preparation, planting and flood irrigation. Bed without soil loosening consisted of no-till planting in March on a PRB with 100% stubble cover (approximate 3.2 t ha^{-1}), furrow irrigation, and harvesting in July. Bed with soil loosening consisted of cutting and loosening the bottom of the bed with the two-edge, flat and V-shaped cutter, respectively, followed immediately by no-till planting in March, furrow irrigation, and harvesting in July. The operation sketch of the bed with soil loosening treatments and the operation schedules of the five treatments are shown in Fig. 2 and Table 2.

The experiment was designed as a randomized block design with three replications. Each plot was 8 m wide and 20 m long. The schematic diagram of the field layout design is presented in Fig. 3. The water volume

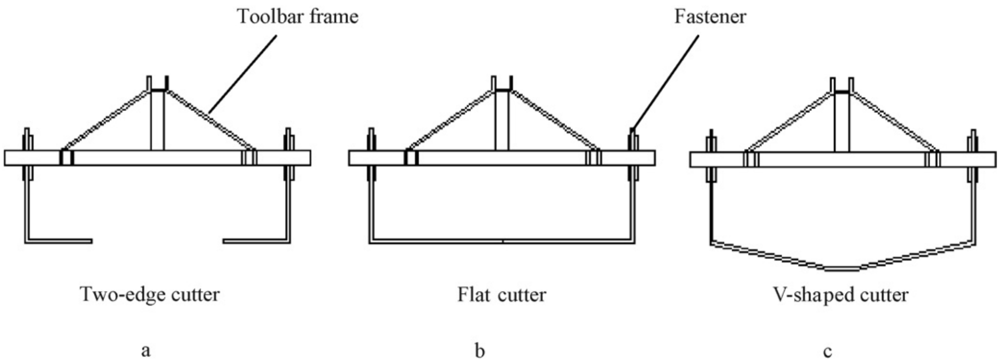

Fig. 1. Schematic diagram of the CAU designed soil loosening cultivator with three kinds of cutters.

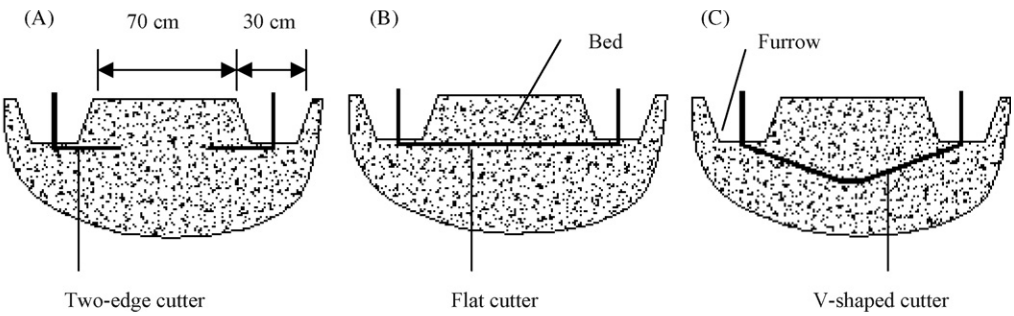

Fig. 2. The operation sketch map of soil loosening machine with two-edge, flat and V-shaped cutter.

Table 2
The operation schedules for five treatments in 2005 and 2006

Treatment	Schedule
TT	Ploughing, leveling (middle of March)–planting of spring wheat (end of March)–flood irrigation (middle of April)–chemical weed controlling (beginning of May)-flood irrigation (middle of May)–flood irrigation (middle of June)–harvesting (end of July)–fallowing to March, next year
NL	No-till planting of spring wheat (end of March)–furrow irrigation (middle of April)–chemical weed controlling (beginning of May)–furrow irrigation (middle of May)–furrow irrigation (middle of June)–harvesting (end of July)–fallowing to March, next year
TC	Soil loosening by two-edge cutter, no-till planting of spring wheat (end of March)–furrow irrigation (middle of April)–chemical weed controlling (beginning of May)–furrow irrigation (middle of May)–furrow irrigation (middle of June)–harvesting (end of July)–fallowing to March, next year
FC	Soil loosening by flat cutter, no-till planting of spring wheat (end of March)–furrow irrigation (middle of April)–chemical weed controlling (beginning of May)–furrow irrigation (middle of May)–furrow irrigation (middle of June)–harvesting (end of July)-fallowing to March, next year
VC	Soil loosening by V-shaped cutter, no-till planting of spring wheat (end of March)–furrow irrigation (middle of April)–chemical weed controlling (beginning of May)–furrow irrigation (middle of May)–furrow irrigation (middle of June)–harvesting (end of July)–fallowing to March, next year

TT: traditional tillage; NL: bed without soil loosening; TC: bed with soil loosening by two-edge cutter; FC: bed with soil loosening by flat cutter; VC: bed with soil loosening by V-shaped cutter.

per irrigation in traditional tillage was 1800 m^3 ha^{-1} (the most popular practice used by farmers), and in PRB treatments, the water volume was 1050 m^3 ha^{-1} per irrigation according to the research conducted by GAAS (2004). The results showed that in 1 m wide bed planting system at the experimental site, the water volume of 1050 m^3 ha^{-1} per irrigation provided the highest spring wheat yields and water use efficiencies in comparison with 900, 1200, 1500 and 1800 m^3 ha^{-1} per irrigation during the experimental years from 2002 to 2004. The amount of irrigation water applied to each treatment was measured by the V notch weir in water supply channel (Fig. 3.). Planting dates were 22 March and 25 March and harvesting dates were 24 July and 28 July, respectively, for 2005 and 2006. In both 2005 and 2006, the spring wheat variety was Longfu 2 with a seeding rate of 450 kg ha^{-1}, and fertilizer was applied at the rate of 225 kg N ha^{-1} and 180 kg P ha^{-1}.

In PRB treatments, the bed was formed in 2004 with the width of 100 cm, furrow to furrow. The surface bed width was 70 cm with a furrow depth of 15 cm, and five rows of spring wheat were planted on the top of the beds. The space between each row on the bed was 15 cm, while the row space in traditional tillage was 18 cm, which is the most common practice in Zhangye.

2.3. Measurements

The impact of soil loosening and three kinds of cutters was assessed by changes in water content, bulk density, soil temperature, plant characters, yield, water use efficiency, power and fuel consumption. Volumetric water content of the five treatments was measured at depths from 0 to 100 cm in April (seedling stage), May (jointing stage) and June (heading stage) after irrigation (Fig. 4). For each treatment, volumetric water content was estimated from measurements at the center of the bed and 25 cm from the edge. For soil moisture and bulk density, three soil samples were taken from each plot using steel tubes (54 mm × 75 mm), which were weighed wet, dried in a fan-aided oven set at 105 °C for 48 h, and weighed again to determine soil water content and bulk density (Liu et al., 2004).

Soil temperature was recorded at 5, 15 and 25 cm soil depths at 08:00 ($T_{08:00}$), 14:00 ($T_{14:00}$) and 20:00 ($T_{20:00}$). Mean daily soil temperature (T) was estimated by (Mao et al., 1998):

$$T = \frac{(2 \times T_{08:00} + T_{14:00} + T_{20:00})}{4} \tag{1}$$

Spring wheat yields were determined by manual harvesting, threshing and air-drying grain from three 1 m^2 areas of each plot and the following indices of yield components were also measured: grains per spike, kernel weight (g) and harvest index (Li et al., 2004).

Evapotranspiration (ET) was calculated using the formula:

$$\mathrm{ET} = P + I + S_g - D - R_f - \Delta W \tag{2}$$

P = rainfall (mm), I = irrigation (mm), S_g = groundwater contribution to plant available water (mm), D = deep drainage into groundwater (mm), R_f = surface runoff (mm), ΔW = change of soil water content (mm).

ΔW was estimated by calculating the differences of total soil water content of the 100 cm soil profile

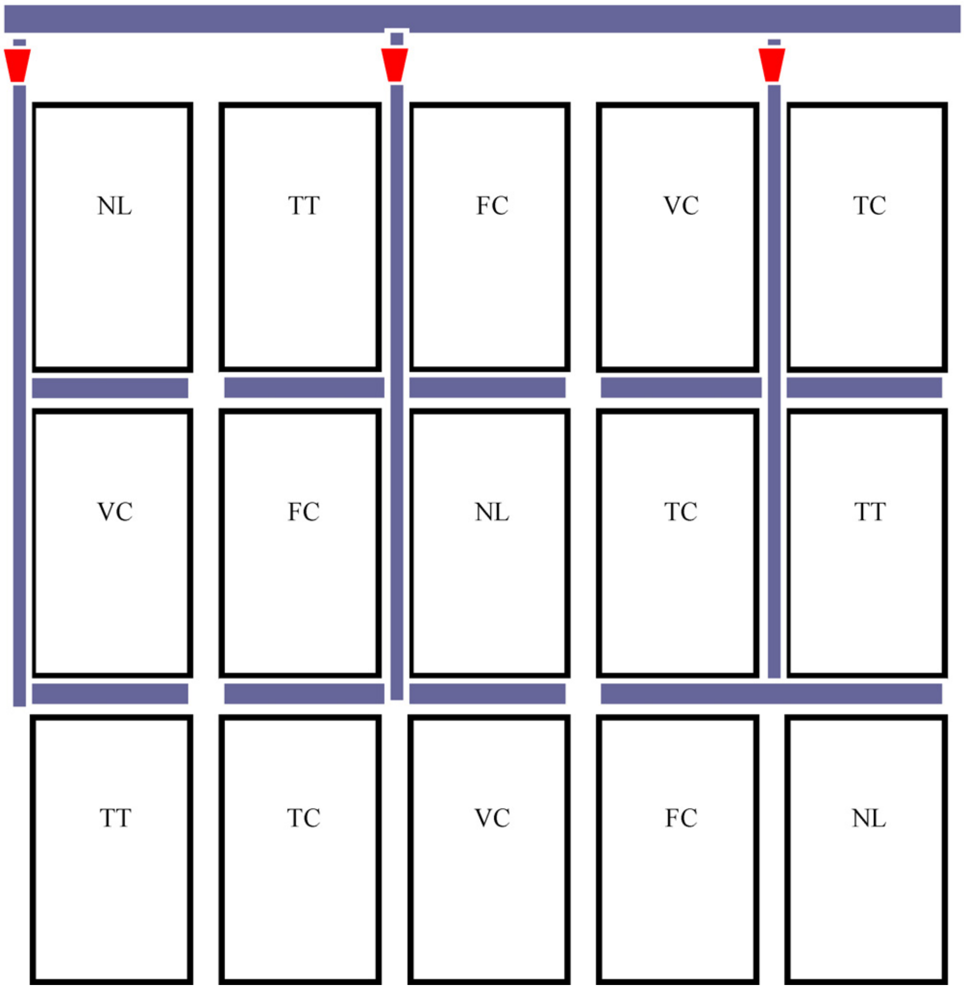

Fig. 3. The schematic diagram of the field layout. TT: traditional tillage; NL: bed without soil loosening; TC: bed with soil loosening by two-edge cutter: FC: bed with soil loosening by flat cutter; VC: bed with soil loosening by the V-shaped cutter ▼: V notch weir; ▬: water supply channel.

determined during the growing period. The capillary contribution from groundwater to the crop root zone (S_g) was negligible because the ground water table is more than 5 m below the bed. Surface water runoff (R_f) was also very small under the semi-arid conditions (Kang et al., 2000). Deep drainage D was estimated using the method developed by Grimes et al. (1992), but values were low and we concluded that drainage had only limited effect on water use efficiency.

Water use efficiency (WUE) was estimated by calculating the yield produced per cubic meter of evapotranspiration (ET):

$$\mathrm{WUE} = \frac{\mathrm{yield}}{\mathrm{ET}}. \quad (3)$$

Fuel consumption was measured directly by a 13.5 kW four-wheel tractor equipped with the CTM-2002B tractor performance monitor (Serrano et al., 2003). Power consumption was assessed by measuring rolling resistance of the 13.5 kW tractor and draft of soil loosening cultivator, by towing the operating unit with a secondary 15 kW tractor coupled to it by a pull sensor belonging to CTM-2002B (He, 2004). For both fuel and power consumption measuring, the soil loosening speed was 4.29 km h^{-1}.

2.4. Statistical analysis

Mean values were calculated for each of the measurements, and ANOVA was used to assess the effects of soil loosening on the measured variables. When ANOVA indicated a significant F-value, multiple comparisons of annual mean values were performed by the least significant difference method

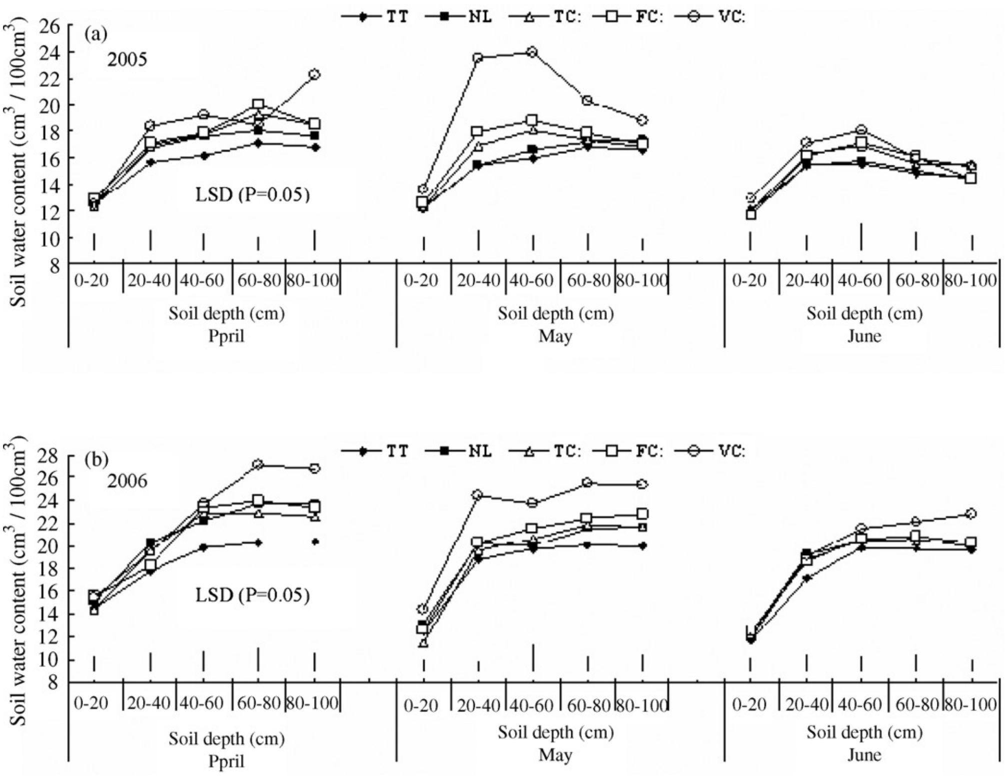

Fig. 4. Mean volumetric water content to the depth of 100 cm for five treatments in April, May and June (2005 and 2006). Soil samples were taken 3 days later after irrigation.

(LSD) (Berzsenyi et al., 2000). The SPSS analytical software package was used for all of the statistical analyses.

3. Results

3.1. Water content

After irrigation, the water content of the bed is one of the most important variables to evaluate the effectiveness of soil loosening for improving lateral water infiltration. The measurements carried out in 2005 and 2006 are shown in Fig. 4.

In April, May, and June of 2005 and 2006, the volumetric water content was lowest for traditional tillage (TT) and the bed without soil loosening (NL). On the loosened beds, the two-edge cutter (TC) and the V-shaped cutter (VC) treatments produced the lowest and the highest soil moisture, respectively, while the flat cutter (FC) showed the intermediate water content. Differences were most pronounced for layers below 40 cm depth. In April, volumetric water content measured for 0–20 cm depth was similar among treatments, but differed from 20 to 100 cm depth in both 2005 and 2006. Compared with TT, PRB treatments significantly ($P = 0.05$) enhanced water content by 12–20% for the sampled layers between 40 and 100 cm depth. Overall, loosening treatments increased water content by 8% in 2005 and 2% in 2006 for 0–100 cm depth, respectively, compared to bed without soil loosening. In May 2005, the volumetric water content for 20–40 and 40–60 cm depths in PRB treatments was 18.9 and 20.8% higher than on traditional tillage, which is significant at $P < 0.05$. In 2006, increases of water content were also significant at those depths. In both years, water content of the top 100 cm soil layer in loosening treatments was 12% (2005) and 6% (2006) higher than in beds without soil loosening, respectively. A similar result was found in June after irrigation. PRB treatments contained 4.9 and 6.6% more water in 0–100 cm layer than traditional tillage in 2005 and 2006, respectively. In all other soil layers the differences were not significant. Overall, loosening treatments improved water content by 6.3% in 2005 and 1.9% in 2006 for 0–100 cm depth relative to bed without soil loosening, respectively. The distribution of water was also more uniform on the treated beds. In 2005, the ratios of soil water content at the center and

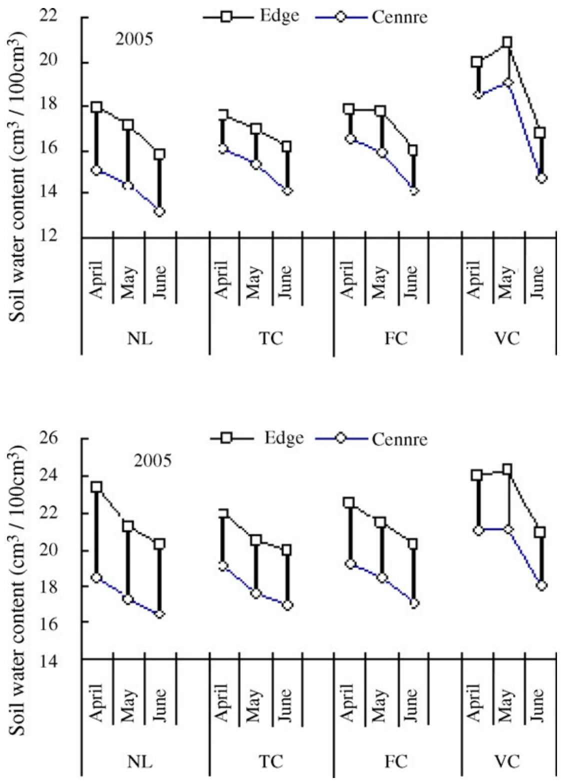

Fig. 5. Mean volumetric water content to the depth of 100 cm in bed's edge and center for four PRB treatments in April, May and June (2005 and 2006). Soil samples were taken 3 days later after irrigation.

edge of the loosened beds were higher (>0.9) than on non-loosened beds (<0.85) throughout the growing season. In 2006, water content in the center was also similar across the beds with soil loosening treatments (Fig. 5).

3.2. Bulk density

Table 3 shows the range of soil bulk density values found under different treatments to depth of 30 cm. After soil loosening, two-edge, flat and V-shaped cutter decreased the bulk densities of beds in 0–30 cm depth by 2–6% compared to the values in beds before soil loosening. Loosening treatments were particularly effective in 10–20 cm depth and most pronounced for the V-shaped cutter. Furthermore, the bulk density differences between the beds and furrows in 0–30 cm depth were large in loosened beds. This created a condition where vertical infiltration, i.e. water losses in the furrows, is minimal, but infiltration into the loosened soil of the bed is promoted.

3.3. Soil temperature

Soil temperature is important for the germination and growth of spring wheat after planting, because the outside temperature in northwest China is still very low in March and April. Fig. 6 shows the average of daily

Table 3
Treatment effects on soil bulk density for 0–30 cm depth (Mg/m^3)

Soil depth (cm)	2005 (bed)			2006 (bed)		
	TC	FC	VC	TC	FC	VC
2005, 2006: before soil loosening						
0–10	1.28 a	1.22 a	1.24 a	1.25 a	1.21 a	1.24 a
10–20	1.27 a	1.30 a	1.32 a	1.25 a	1.26 a	1.24 a
20–30	1.32 a	1.31 a	1.30 a	1.31 a	1.29 a	1.28 a

Soil depth (cm)	TT	NL		TC		FC		VC	
		Bed	Furrow	Bed	Furrow	Bed	Furrow	Bed	Furrow
2005, 2006: after soil loosening									
2005									
0–10	1.29 ab	1.27 ab	1.40 c	1.26 ab	1.42 c	1.20 a	1.35 bc	1.21 a	1.38 c
10–20	1.30 bc	1.30 bc	1.38 cd	1.23 ab	1.42 d	1.22 ab	1.40 cd	1.19 a	1.39 cd
20–30	1.38 ab	1.32 ab	1.38 ab	1.32 ab	1.37 ab	1.30 a	1.41 b	1.28 a	1.38 ab
2006									
0–10	1.33 b	1.24 ab	1.48 c	1.24 ab	1.52 c	1.18 a	1.45 c	1.20 a	1.47 c
10–20	1.32 c	1.28 bc	1.43 d	1.20 ab	1.48 d	1.19 ab	1.43 d	1.14 a	1.44 d
20–30	1.39 bc	1.31 ab	1.42 c	1.30 ab	1.42 c	1.27 a	1.40 bc	1.27 a	1.43 c

TT: traditional tillage; NL: bed without soil loosening; TC: bed with soil loosening by two-edge cutter; FC: bed with soil loosening by flat cutter; VC: bed with soil loosening by V: shaped cutter. Means within a row in the same soil layer followed by the same letters are not significantly different ($P = 0.05$).

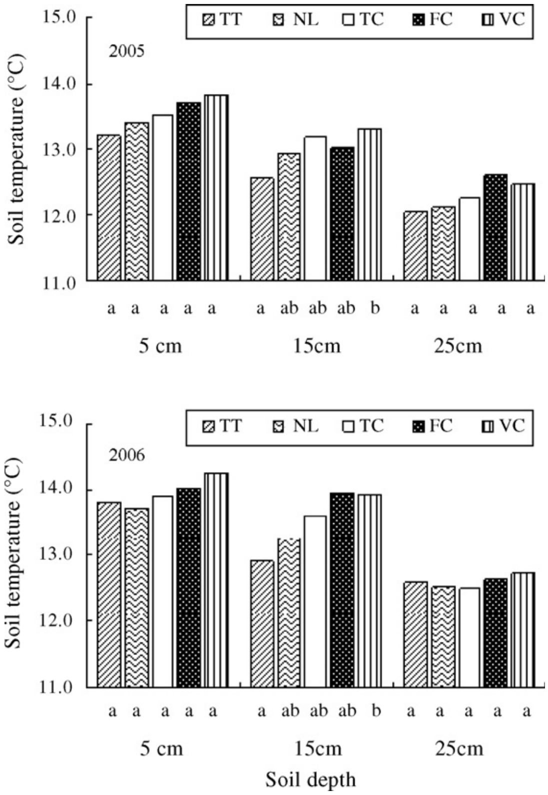

Fig. 6. Soil temperature measured over five treatments at 5, 15 and 25 cm soil depths. Means within each depth and year followed by the same letter were not significantly different ($P = 0.05$).

soil temperature for 30 days after planting in the five different treatments at 5, 15 and 25 cm depths.

In the same soil layer, treatments which decreased soil bulk density normally showed an increase of soil temperature. In loosening depth of 15 cm, TC and VC treatments with 6.9% of lower bulk density (Table 3) increased soil temperature by up to 0.3 °C in 2005 compared to bed without soil loosening. In 2006, the 9.0% lower soil bulk density in FC and VC treatments followed with a 0.7 °C higher soil temperature relative to bed without soil loosening. The soil temperature advantages in bed with soil loosening treatments were not evident in 5 and 25 cm depths.

3.4. Seedling emergence

The seedling emergences for traditional tillage in 2005 and 2006 were significantly ($P = 0.05$) better than the PRB treatments (Table 4). Bed with soil loosening treatments showed significant improvements for the flat and V-shaped cutter, enhancing seedling emergence by up to 6% compared to the bed without soil loosening. However, seedling emergence was still ~15% lower than on traditional tillage.

3.5. Growth

3.5.1. Jointing to heading stage

Spring wheat growth on traditional tillage was slower than that of PRB treatments (Table 5), possibly because of the lower soil moisture and the effects of less favorable soil temperature regime during seedling development. Soil loosening improved plant condition, especially in the root zone, where soil loosening increased dry weight by 7–11% compared to traditional tillage. These improvements are significant ($P = 0.05$) and show that soil loosening was effective in facilitating root development by increasing soil moisture and temperature and decreasing bulk density. On beds without soil loosening, differences of plant growth were inconspicuous in comparison to traditional tillage.

3.5.2. Maturing stage

PRB treatments generated yields which were up to 9% higher than on traditional tillage. In 2006, yields of spring wheat were lower for all treatments than in 2005 because of less rainfall and later planting (Table 6). Yield for traditional tillage decreased by 13% in 2006 as compared with 2005, while PRB treatments were reduced by just 6%. The smaller decline of yields in 2006 shows that PRB farming systems not only improve yields, but also maintain more stable yields during drought years. Some other aspects of plant maturing were also affected by the planting system. Grains per spike and

Table 4
Seedling emergence of spring wheat (plant m^{-2}) during 2005 and 2006

Year	Planting date	TT	NL	TC	FC	VC
2005	22nd March	734 a	633 b	621 b	635 b	668 c
2006	25th March	687 a	578 b	586 bc	604 c	592 c

TT: traditional tillage; NL: bed without soil loosening; TC: bed with soil loosening by two-edge cutter; FC: bed with soil loosening by flat cutter; VC: bed with soil loosening by V-shaped cutter. The data were measured 15 days after planting. Means within a row in the same year followed by the same letters are not significantly different ($P = 0.05$). In NL, TC, FC and VC treatments, the m^2 in unit (plant m^{-2}) refers to the area of bed and furrow combined.

Table 5
Leaf area (cm^2 $plant^{-1}$), plant height (cm), plant dry weight (g $plant^{-1}$) and root dry weight (g per 100 plants) at 0–20 cm depth of spring wheat for five treatments from joint to heading stage in 2005 and 2006

Year	Treatment	Leaf area	Plant height	Plant dry weight	Root dry weight
2005	TT	39.8 a	66.8 a	28.7 a	732 a
	NL	41.1 a	66.0 ac	28.3 a	704 b
	TC	42.8 b	70.4 b	31.7 b	743 c
	FC	45.8 c	65.1 c	27.7 a	829 d
	VC	48.5 d	68.2 d	30.9 c	786 e
2006	TT	42.7 a	64.2 a	34.7 a	757 a
	NL	43.4 a	66.8 b	36.6 b	795 b
	TC	45.6 b	65.7 b	38.8 c	834 c
	FC	41.7 c	66.5 b	36.8 b	804 d
	VC	45.2 b	71.5 c	37.4 b	876 e

TT: traditional tillage; NL: bed without soil loosening; TC: bed with soil loosening by two-edge cutter; FC: bed with soil loosening by flat cutter; VC: bed with soil loosening by V-shaped cutter. The data were measured on 21st May in 2005 and 24th May in 2006. Means within a column in the same year followed by the same letters are not significantly different ($P = 0.05$).

kernel weight were enhanced by 3–6% on PRB treatments.

3.6. Water use efficiency

Water use efficiency is one of the most important indices for the assessment of water-saving effect of soil loosening. During the two crop cycles, PRB treatments required less irrigation water, while yields increased. Water use was apparently improved by furrow irrigation system, loosened soil structure and the benefits of high standing stubble with straw cover (Sarkar and Singh, 2007). As a result, water use efficiencies for PRB treatments were significantly ($P = 0.05$) higher than on traditional tillage for both years of the test. On PRB treatments, the bed with soil loosening treatments slightly enhanced (1%) the mean water use efficiency compared to bed without soil loosening, and the discrepancies among them were not significant.

3.7. Power and fuel consumption

Power and fuel consumption of the soil loosening machine was tested to assess the cost effectiveness of the three different cutters (Fig. 7). At the operation speed of 4.29 km h^{-1}, the V-shaped cutter required most power and fuel, but differences to the two-edge and flat cutter were small (1.4 kW, 0.84 l ha^{-1}).

4. Discussion

The tests conducted for this study on the use of soil loosening on permanent raised-beds showed that crop yield and water use efficiency can be improved significantly compared to traditional tillage. The results contribute to other recent research on the advantages of permanently raised beds (e.g. Hari et al., 2005; Kukal et al., 2005). The advantage of PRB can be explained by the improvement of soil physical and chemical

Table 6
Grains per spike, kernel weight (g), harvest index, yield (kg ha^{-1}) of spring wheat in maturing stage during 2005 and 2006

Year	Treatment	Grains per spike	Kernel weight	Harvest index	Yield
2005	TT	48 a	46.2 a	0.44 a	6164 a
	NL	45 b	49.7 b	0.42 a	6114 a
	TC	52 c	47.3 ac	0.46 a	5764 b
	FC	54 c	48.7 bc	0.43 a	6483 c
	VC	52 c	48.4 bc	0.44 a	6436 c
2006	TT	46 a	47.3 a	0.44 a	5355 a
	NL	47 a	46.2 ab	0.46 a	5624 b
	TC	50 b	45.2 b	0.43 a	5738 bc
	FC	47 a	48.9 c	0.45 a	5926 cd
	VC	51 b	50.1 c	0.45 a	6012 d

TT: traditional tillage; NL: bed without soil loosening; TC: bed with soil loosening by two-edge cutter; FC: bed with soil loosening by flat cutter; VC: bed with soil loosening by V-shaped cutter. Means within a column in the same year followed by the same letters are not significantly different ($P = 0.05$).

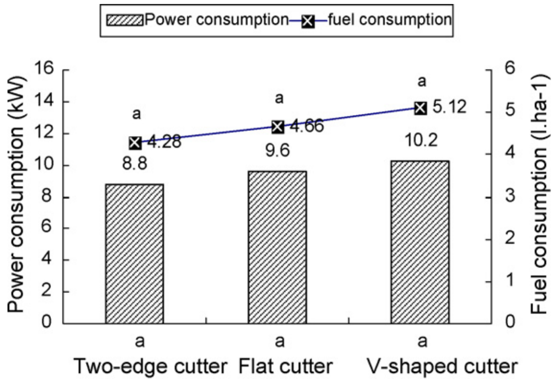

Fig. 7. Power consumption and fuel consumption for soil loosening machine with two-edge, flat and V-shaped cutter in Zhangye. The operation speed of soil loosening machine was 4.29 km h^{-1}. Means within power consumption or fuel consumption followed by the same letter were not significantly different ($P = 0.05$).

properties (Hulugalle and Entwistle, 1997; Agustin et al., 2002), which in drylands has a major effect on soil moisture (Humphreys et al., 2001).

The soil loosening was associated with increased and more uniform lateral penetration of irrigation water into beds. This demonstrates that water losses from downward drainage out of the furrow were reduced while lateral infiltration of rainwater from furrows into the bed during natural rainfall was improved. During the seedling stage after irrigation (April), TC, FC and VC increased mean volumetric water contents of beds to 100 cm depth by up to 21% in 2005 compared to no loosening (Fig. 4). In 2006, the loosening effects on soil moisture of two-edge and flat cutter were inconspicuous, but the V-shaped cutter significantly improved water content. In jointing stage after irrigation (May), higher volumetric water contents were also achieved by soil loosening, again especially the V-shaped cutter. A similar trend continued in the heading stage after irrigation (June), but the soil water content advantages of TC, FC and VC were not significant ($P = 0.05$). The ratios of soil water content from center to edge were more uniform for the TC, FC and VC treatments, indicating that all the cutters, especially the V-shaped cutter, effectively facilitated water infiltration from furrow to the center of the bed. The positive effect of soil loosening found in this study is consistent with a ridge-loosening experiment conducted in northeast China (Guo and Liu, 2005).

The benefits of soil loosening were not limited to soil moisture, but also improved soil temperature during the experimental years compared to raised-beds without loosening (Fig. 6). The results are in accordance with those of Moroizumi and Horino (2002) who recorded higher soil temperature at 4 and 14 cm soil depths under tillage than untilled conditions. The improved soil temperature was due to soil disturbance under bed with soil loosening treatments. The porous soil created by soil loosening tended to dry faster and warm more quickly in the spring. Of the three cutters, the V-shaped one offered the most benefits to soil temperature, especially in the 15 cm soil depth.

In beds with soil loosening treatments, the cropping zone only accounted for about 70% of total experimental plot area because crops were just planted on the beds. Therefore, seedling numbers on traditional tillage, which extended to the entire test area, were greater than on beds with soil loosening treatments (Table 4). However, on the treated PRB beds the benefits of soil loosening compensated for this initial shortfall in plant density. Plant character indices of spring wheat were also improved on beds with soil loosening treatments,

Table 7
Mean water use efficiencies (kg ha^{-1} mm^{-1}) for five treatments in 2005 and 2006

Year	Treatment	Rainfall (mm)	Total irrigation (mm)	ΔW (mm)	D (mm)	WUE
2005	TT	95	540	38.7	31.6	9.7 a
	NL	95	315	28.4	28.6	14.8 b
	TC	95	315	40.5	28.0	13.6 c
	FC	95	315	34.7	43.2	16.2 b
	VC	95	315	36.4	38.6	15.8 b
2006	TT	73	540	42.5	40.6	8.7 a
	NL	73	315	33.4	47.8	15.0 b
	TC	73	315	36.4	46.3	15.2 b
	FC	73	315	40.7	56.8	15.9 b
	VC	73	315	38.5	58.9	16.4 b

TT: traditional tillage; NL: bed without soil loosening; TC: bed with soil loosening by two-edge cutter; FC: bed with soil loosening by flat cutter; VC: bed with soil loosening by V-shaped cutter. Means within a column in the same year followed by the same letters are not significantly different ($P = 0.05$).

especially for the V-shaped cutter (Table 5). The 2-year data of yields at Zhangye supported earlier findings of Yang (2002), who concluded that for spring wheat in cold and arid areas, faster crop growth was an important factor to result in higher crop yield.

The data in Tables 6 and 7 show that although mean yield and water use efficiency in beds with soil loosening treatments were higher than in beds without soil loosening, only the flat and V-shaped cutter improved crop yield and WUE in both 2005 and 2006. The two-edge cutter just loosened the two sides of the bed's bottom and the slight soil disturbance could not maintain the consistent advantages of soil moisture, soil temperature and bulk density in both years. Therefore, seedling numbers and kernel weight were reduced, which led to lower spring wheat yield in TC treatment relative to FC and VC treatments. This indicates that slight soil loosening by a two-edge cutter cannot achieve the benefits of soil loosening by a flat or V-shaped cutter. The importance of cutter design for effective soil loosening confirms the results of Ma (2005), which showed that the cutters with slight soil loosening could not help much to increase crop yield and WUE.

The analysis of soil moisture, bulk density, soil temperature, yield, water utilization, power and fuel consumption, showed clearly that soil loosening could effectively improve lateral water infiltration and WUE, ameliorate the soil temperature regime, and raise and stabilise yields on PRB farming systems in northwest China. With a small additional cost for power and fuel consumption, bed with soil loosening by V-shaped cutter offers the highest benefits of the three tested cutters.

5. Conclusions

The key result of this study is that soil loosening is suitable as a new farming technique to alleviate slow lateral water infiltration into the raised-bed and increase crop yield for wide raised-beds. Despite slightly higher power and fuel consumption, the integrated effects of bed with soil loosening by V-shaped cutter were the best among three tested. Through adopting bed with soil loosening by V-shaped cutter, 13% of irrigation water could be saved, WUE efficiency improved by 8% and yields increased by 6% under PRB farming systems. The study also confirmed earlier works that permanent raised-beds are effective in improving water use efficiency and yield. Soil loosening could therefore be a significant improvement for current farming on permanent raised-beds, and make an important contribution to increase the regions food production while accommodating the water shortage of the semi-arid climate. While the initial results on the use of soil loosening are encouraging, more research on the soil loosening frequency and the relationships between soil loosening, soil quality, WUE and crop yields is required to develop appropriate farming practices for the variable environmental conditions and farming practices in northwest China.

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