Soil Tillage, Conservation & Management

Permanent Beds vs. Conventional Tillage in Irrigated Arid Central Asia

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ABSTRACT

Limited or no tillage with residue retention on the soil surface has had mixed success in irrigated agricultural systems. The effects of tillage and crop residue management on soil properties and crop yields were studied on a silt loam soil using a rotation of winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) for 2 yr, followed by cotton (*Gossypium hirsutum* L.) for 2 yr. Permanent beds (PB) with limited reshaping and conventional tillage (CT) were compared, each with both 25% residue retention on a mass basis (R25) and 100% residue retention (R100). There was greater soil compaction and consolidation in the 0.2- to 0.3-m depth with the PB system regardless of residue retention practice. Compared with the CT system and the PB+R25 treatment combination, the PB+R100 treatment combination increased the amount of water-stable macroaggregates, however only in the fourth year. The soil organic C in the 0- to 0.4-m depth increased at 0.70 Mg ha^{-1} yr^{-1} in PB+R100 vs. 0.48 Mg ha^{-1} yr^{-1} in CT+R100. Poor early plant growth and reduced plant population in PB caused decreased water use efficiency (WUE) and irrigation water use efficiency (IWUE) of maize and cotton grown consecutively in 2006 and 2007. Generally, R100 improved IWUE and WUE, except for cotton in 2007. For PB+R100, cotton seed-lint IWUE in 2008 increased to 0.59 kg m^{-3} from 0.41 earlier. Smaller maize and cotton plant populations and cooler soil temperatures at cotton emergence in PB+R100 decreased crop productivity during the first 3 yr.

Crop cultivation under zero or minimum tillage has gained worldwide attention, as substantiated by the expanding cropping area under conservation agriculture (CA) practices, which grew from 57 Mha or 3% of the total arable land globally under cultivation (FAO, 2001) to more than 100 Mha by 2009 (Derpsch and Friedrich, 2009). Conservation agriculture practices so far have mainly been applied under rainfed conditions, and less information is available about CA practices under irrigation (Sayre and Hobbs, 2004). In Pakistan, the area under zero tillage increased exponentially from 1997 to 2003 owing to improved yields, increased water and fertilizer use efficiency, and reduced weed infestation (Khan, 2002; Akhtar, 2006). Due to the intensive advocacy of the Rice–Wheat Consortium for the Indo-Gangetic Plains, the area under zero tillage in India has increased to 2 Mha, which was credited for higher yields, reduced production costs, and resource savings (Gupta et al., 2003).

In the Central Asian states, intensive and highly mechanized irrigated agriculture was introduced during the Soviet era, especially in Uzbekistan, which specialized in cotton production. Cultivation technologies were developed through experiments and used by the production farming units as compulsory guidelines. Although developed during the collective farming-system era, various practices still dominate the mindset of agricultural specialists. The current practices are often assessed as an overuse of resources, and similar levels of production could be achieved with a more rational use of inputs and use of farming practices that increase input use efficiency and simultaneously reduce the potential for environmental hazards (FAO, 2001).

Cotton and winter wheat are the major crops in Uzbekistan, followed by maize, vegetables, fruits, and others. Owing to its deep continental geographic location, the country has little and erratic precipitation. Thus, agricultural production in the country, as in the whole of Central Asia, is predominantly based on irrigation, which makes irrigation water supply the prevailing factor limiting crop yields in the region. Irrigated land, though comprising only about 10% of the territory in Uzbekistan, produces >95% of the total agricultural output and is of paramount significance for the agricultural and economic productivity of the country.

At present, by state order, cotton and wheat occupy annually about 70 to 80% of the irrigated cropland in Uzbekistan. Only following the harvest of winter wheat (usually in June) can the freed land be used by farmers according to their choice, which they exercise even though the remaining growing season is restricted to about 3 to 4 mo. This "double season" is feasible with a restricted choice of crops and cultivars. Thus, short-maturity crops such as maize, pulses, sunflower (*Helianthus annuus* L.), or vegetables after the harvest of winter wheat are produced not only by farmers in Uzbekistan but also other Central Asian countries. The cultivation of summer crops includes irrigating quickly after the winter wheat harvest, followed by soil preparation, fertilization, and planting, which are

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Abbreviations: CA, conservation agriculture; CT, conventional tillage; ET, evapotranspiration; IWUE, irrigation water use efficiency; PB, permanent beds; POM_C, particulate organic matter; R100, 100% residue retention on a mass basis; R25, 25% residue retention on a mass basis; SOC, soil organic carbon; WUE, water use efficiency; ZT, zero tillage.

not possible without irrigation after the wheat harvest due to dry and hard soil. Hence, delay due to the irrigation event slows planting and results in late crop maturity or even premature harvest when a killing frost occurs in autumn. The use of short-maturing cultivars (e.g., FAO 190 or FAO 210) is crucial to the winter wheat–summer crop system because prolonged low temperature or sporadic killing frost may occur in October and substantially decrease the yield of an unripe crop.

There is little information on PB and zero tillage (ZT) CA practices in the irrigated agriculture of Central Asia. One possible advantage of these systems is the reduction or elimination of the time needed for tillage before planting a summer crop after wheat. Recent investigations with a winter wheat–maize–cotton rotation under controlled experimental conditions and irrigation in northwest Uzbekistan on a sandy loam soil showed that CA practices could lead to similar benefits as in rainfed areas (Egamberdiev, 2007; Tursunov, 2009). The findings showed that both PB, with superficial reshaping as needed before planting of each succeeding crop, and ZT increased C and N sequestration in the soil, slowed down soil salinity development, and improved soil aggregation, soil fauna, stand establishment, and biomass production. Furthermore, cumulative gross margin analyses showed higher gross margins for all CA practices compared with the CT treatments. Dominance analysis revealed an advantage of the conservation practices over CT because of the lower total variable cost and higher gross margins (Tursunov, 2009).

Soil organic matter (OM) and soil structure are strongly related because OM binds mineral particles into stable aggregates. This mechanism can be enhanced under CA compared with CT systems (Six et al., 1999). The OM content and soil aggregate distribution and aggregate stability have therefore been proposed as important soil quality indicators (Christensen, 1992). This study compared PB vs. CT combined with two levels of crop residue retention in northeast Uzbekistan on a silt loam soil that represents about 8 Mha of irrigated land in arid Central Asia (Program Facilitation Unit, 2008). Field experiments were performed during 4 yr (2004–2008). The objectives of the study were to determine the effects of PB and CT systems with different residue retention practices on (i) the dynamics of soil properties such as bulk density, porosity, macroaggregation, water infiltration, soil organic C (SOC), and particulate organic matter (POM_C), and (ii) crop water use and irrigation water use efficiencies (WUE and IWUE, respectively) by the crops in rotation.

MATERIALS AND METHODS

Study Area

The 4-yr field experiment was conducted at the Central Experiment Station of the Uzbekistan Cotton Research Institute (CES-CRI, 41°42′ N, 69°49′ E, 623 m elevation above mean sea level) near Tashkent. The CES-CRI is located in the northeast of the Uzbekistan Cotton Belt. The soil, a silt loam

Table 1. Soil texture and particle size distribution of the Calcic Xerosol near Tashkent (Central Experiment Station of Uzbekistan Cotton Growing Research Institute).

Soil layer	Sand	Clay	Silt	Texture
cm		%		
0–30	19	27	54	silt loam
30–50	21	27	52	silt loam

Calcic Xerosol in the FAO taxonomy (FAO, 2003), is known in the Russian taxonomy still used in Uzbekistan as an old irrigated typical Sierozem. Its texture is uniform with depth (Shamsiev, 2003), and it is derived from loess, either in place or in alluvial deposits. The water table is >15 m deep, ensuring an automorphic type of soil formation. Some chemical and physical characteristics of the soil are given in Tables 1 and 2.

The climate in the study area is strongly continental and semi-arid, with an annual mean precipitation of 498 mm, which falls mainly outside the summer growing season. The annual mean air temperature is 13°C, but maxima of about 40°C (July) and minima of about –20°C (January) were recorded during the study period. Frost and cold spells can occur from October onward. Spring is short but summer is long, hot, and dry. The cold, short winters do not exceed more than 2 to 3 mo yr^{-1} (Chub, 2000).

Experimental Design and Data Collection

A two-factor, split-plot experiment was implemented, with soil tillage as the main factor and crop residue retention level as the split factor (Table 3). The two tillage treatments (PB and CT) were completely randomized, as were the two residue retention levels (R25 and R100). The blocks were replicated four times. Under CT, cotton and maize crops were cultivated to the 15- to 17-cm soil depth in the interrow two to five times during the season. The subplots were 4.8 by 40 m in size. The reported data correspond to the following crops: winter wheat and maize in rotation for 2 yr followed by cotton (2 yr).

- The 2004–2005 winter wheat season was a preparatory season, so is not shown in Table 3. In autumn 2004, irrigated winter wheat cultivar Mars was broadcast planted at the rate of 200 kg ha^{-1} (445 seeds m^{-2}) and incorporated by cultivator into cotton stubble (the common practice in Uzbekistan) on 2 Nov. 2004 in the plots that would later be used for each of the two tillage treatments (CT and PB). Winter wheat was harvested on 3 July 2005. The first soil tillage and residue management treatments were established with maize grown in 2005 after winter wheat.
- A short-duration maize cultivar Uzbekistan-306MV (97 d, FAO 370) was seeded at the rate of 25 kg ha^{-1} (9 seeds m^{-2}) with 60-cm row spacing on 12 July 2005 as a summer crop after the 2004–2005 winter wheat. It was harvested as grain on 28 Oct. 2005.

Table 2. Soil chemical characteristics of the Calcic Xerosol near Tashkent (Central Experiment Station of Uzbekistan Cotton Growing Research Institute), where EC is saturation paste extract electrical conductivity, TDS is total dissolved salts, and SOC is soil organic C.

Soil layer	pH	EC	TDS	SOC	N	P	NO_3	Available P_2O_5	Exchangeable K_2O
cm		dS m^{-1}	g kg^{-1}	%				mg kg^{-1}	
0–10	7.6	0.55	0.28	0.56	0.8	1.2	6.7	35	171
10–20	7.4	0.54	0.27	0.49	0.8	1.1	5.6	29	157
20–30	7.6	0.56	0.28	0.44	0.7	1.0	5.1	25	145
30–40	7.6	0.57	0.27	0.37	0.6	0.9	4.4	24	134

Table 3. Description of treatments for the 2005–2008 seasons, during which tillage and crop residue management treatments were applied.

Treatment	Crop sequence					Tillage treatment	Crop residue management treatment
	2005	2005–2006	2006	2007	2008		
CT+R25	maize	winter wheat	maize	cotton	cotton	conventional	25% residue incorporated
CT+R100	maize	winter wheat	maize	cotton	cotton	conventional	100% residue incorporated
PB+R25	maize	winter wheat	maize	cotton	cotton	permanent beds	25% residue surface applied
PB+R100	maize	winter wheat	maize	cotton	cotton	permanent beds	100% residue surface applied

- Winter wheat cultivar Mars was sown with a drill at the rate of 200 kg ha^{-1} (445 seeds m^{-2}) with 19-cm row spacing on 2 Nov. 2005 and harvested on 26 June 2006.
- A shorter (than 2005) duration maize cultivar Karasu-350 (93 d, FAO 330) was planted at the rate of 30 kg ha^{-1} (11 seeds m^{-2}) with 60-cm row spacing on 14 July 2006 as a summer crop after the 2005–2006 wheat and harvested as grain on 2 Nov. 2006, just before a killing frost was forecast.
- Cotton cultivar Bukhara-102 was seeded on 26 Apr. 2007 at a rate of 60 kg ha^{-1} (45 seeds m^{-2}) with 60-cm row spacing and harvested in September to November 2007. The normal practice in Uzbekistan is to apply extra seed and then thin.
- Cotton cultivar Bukhara-102 was planted on 30 Apr. 2008 at 60 kg ha^{-1} (45 seeds m^{-2}) with 60-cm row spacing and harvested in September to November 2008.

Seventy-five percent of the winter wheat and maize stover as well as cotton stocks were removed manually after the harvest of the panicles, cobs, and raw cotton bolls, leaving 25% of these residues for each crop, which corresponds to present farmer practice. Removing crop residues is a common practice in Uzbekistan due to the high dependence on crop residues as fodder for livestock and the existence of local markets for these residues. This 25% stover retention was determined from detailed weighing in harvested subplots. For the 100% retention treatments, the 75% removed stover was chopped to 7- to 8-cm pieces and spread evenly by hand on the soil surface of the original plots.

A seeder, especially designed for planting on beds (Dashmesh Agricultural Works, Punjab, India), was used for the PB tillage system. The beds and furrows of the PB were reshaped before cropping maize and cotton by deepening the furrows to a depth of 15 cm. Bed width in PB was kept constant at 30 cm during the 4 yr. Soil preparation under CT for all crops included moldboard tilling to the 30-cm depth, harrowing to 10 to 12 cm, and land leveling.

Winter wheat and maize seeds were preplant treated with 0.018 kg a.i. tebuconazole (α-[2-(4-chlorophenyl)ethyl]-α-(1,1-dimethylethyl)-1*H*-1,2,4-triazole-1-ethanol) Mg^{-1} seed. Cotton seed was treated with 3.0 kg a.i. bronopol (2-bromo-2-nitro-1,3-propanediol) Mg^{-1} of seed. Fertilizer application rates for both CT and PB treatments were based on the fertilization recommendations established for irrigated winter wheat, short-duration maize, and cotton for CT systems in Uzbekistan. Fertilizer applied to the winter wheat totaled 200 kg N ha^{-1}, 140 kg P ha^{-1}, and 100 kg K ha^{-1}. Nitrogen as urea was manually broadcast in three split applications (20% at planting, 40% at tillering, and 40% at the boot stage) followed by irrigation. Phosphorus as single superphosphate (SSP) and KCl were preplow applied for CT and were banded in the furrow and then incorporated through cultivation when reshaping the beds for the PB.

The chemical fertilizer applied to maize totaled 100 kg N ha^{-1}, 70 kg P ha^{-1}, and 50 kg K ha^{-1}. The SSP and KCl fertilizers were broadcast before soil preparation for maize sowing. Urea was banded for all treatments at the 10- to 12-cm depth in two split applications (at the 4–6- and 10–12-leaf stages of the crop) directly followed by irrigation.

Mineral fertilizer for cotton was 200 kg N ha^{-1}, 140 kg P ha^{-1}, and 100 kg K ha^{-1}. An initial dressing of SSP and KCl was applied at a rate of 100 kg P ha^{-1} and 100 kg K ha^{-1}. The remaining 40 kg P ha^{-1} was banded together with N fertilizer at cotton flowering. Urea was applied in three splits: 50 kg N ha^{-1} before seeding, 75 kg N ha^{-1} at squaring, and the same amount at flowering.

Chemical weed control in cotton and maize was administered through the application of 1.4 kg a.i. ha^{-1} glyphosate [*N*-(phosphonomethyl)glycine] 1 to 2 d before planting, and in winter wheat with 15 g a.i. ha^{-1} tribenuron methyl [methyl 2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)methylamino] carbonyl]amino]sulfonyl]benzoate] at the Zadoks 26 stage. For disease and pest management, 0.02 kg a.i. ha^{-1} esfenvalerate [(*S*)-cyano(3-phenoxyphenyl)methyl (α*S*)-4-chloro-α-(1-methylethyl) benzeneacetate] was applied at Stage 2 of cotton and at the Zadoks 75 stage of wheat development, 0.86 kg a.i. ha^{-1} propargite (2-[4-(1,1-dimethylethyl)phenoxy]cyclohexyl 2-propynyl sulfite) at Stage 5 of cotton development, and 0.25 kg a.i. ha^{-1} triadimefon [1-(4-chlorophenoxy)-3,3-dimethyl-1-(1*H*-1,2,4-triazol-1-yl)-2-butanone] at the Zadoks 58 to 59 growth stage of winter wheat. Maize was not noticeably affected by pests and, therefore, no foliar insecticide or fungicide applications were warranted.

Measurements of the volumetric water content of the soil profile were conducted twice a week and in two replicates during the experiments using a neutron probe to the 160-cm depth in 20-cm increments using the techniques described in Evett et al. (2008). The neutron probe (Model 503DR1.5, CPN International, Concord, CA) was previously calibrated in polyvinyl chloride access tubes for each soil layer (Kamilov et al., 2003; Evett et al., 2007). Crop water use (evapotranspiration, ET) was established using the soil water balance approach on a weekly basis (Ibragimov et al., 2007) as $ET = -\Delta S + P + I + F + R$, where ΔS is the change in water stored in the soil profile (decreases in stored water indicate positive ET), P is precipitation, I is irrigation, F is the flux across the lower boundary of the control volume (1.7-m depth in this case and F positive into the control volume), and R is the sum of run-on and runoff (assumed zero); all terms are in millimeters. The water infiltration rate was measured in each treatment from the volume of water that was added during 6 h to a ring infiltrometer (35-cm diameter and 30-cm height) driven 15 cm into the soil. The sustained water level in the ring was 5 to 7 cm above the soil surface (Forkutsa, 2006).

For irrigation scheduling, the field capacity (F_C) index was used, which was 0.30 m^3 m^{-3} in this soil. For each crop in the rotation, irrigations were scheduled at specific percentages of F_C during each of three plant growth periods, as shown in Table 4. Irrigation water use efficiency (kg m^{-3}) was calculated as the dry grain or seed-lint yield (kg m^{-2}) divided by the irrigation water applied (m^3 m^{-2}). The total water use efficiency (kg m^{-3}) was calculated as the dry grain or seed-lint yield (kg m^{-2}) divided by the ET, which was converted to units of cubic meters per square meter. Because dryland crop yields are often zero in the region, dryland crops were not grown and IWUE was not adjusted for dryland yield. The amount of the irrigation water applied was measured with a trapezoidal weir (U.S. Bureau of Reclamation, 1997).

Soil and Plant Sampling and Analyses

The soil bulk density (ρ_b, Mg m^{-3}) was determined at the end of the vegetation season of each crop using the core method (Blake and Hartge, 1986). For each depth, the mean ρ_b values were used to calculate the oven-dried air-filled porosities, $\phi_a = 1 - (\rho_b/\rho_s)$, where ρ_s is the density of the solid fraction and was determined to be 2.70 Mg m^{-3}.

For each treatment in each of the replicate plots, soil samples were collected at the end of each vegetation season from three locations by sampling the 0- to 40-cm depth in 10-cm increments using a 5-cm-diameter auger. Subsamples were thoroughly mixed, spread, air dried, ground to pass a 0.25-mm sieve, and analyzed for SOC and POM_C contents. Correction for soil compaction to calculate SOC and POM_C was performed according to Sisti et al. (2004). Fractionation of the soil organic matter by particle size was done according to Okalebo et al. (1993).

The aggregate size distribution was determined after dry sieving and the water stability by wet sieving of slaked soil samples (Kemper and Rosenau, 1986). The mean weight diameter (MWD) was used to express the aggregate size distribution after dry and wet sieving (Van Bavel, 1950):

$$\mathrm{MWD} = \sum_{i=0}^{n} d_i w_i$$

where d_i is the mean diameter of the ith size fraction, w_i is the proportion of total sample weight occurring in the ith size fraction, and n is the number of size fractions.

The winter wheat was hand harvested at physiological maturity from three areas of 1 m^2 each in each plot. Due to early frost in October 2005 and a rapid temperature drop to daily means of 10 to 13°C with light but not killing frost in the latter half of October 2006, maize was harvested as grain at the R5 stage for CT and at R3 for the PB treatment in both years. In each year, the timing of harvest was the same for the CT and PB treatments, but maize in the CT treatment was phenologically more advanced. For maize, two adjacent 4.15-m central rows were hand harvested from each plot. Subsamples of ears and stover were oven dried at 70°C for 24 to 72 h, depending on the sample nature, and the ears were then shelled. The dry grain and stover were weighed, and dry matter yields were calculated.

The seed-lint of cotton was hand harvested from a 48-m^2 area in each plot (Uzbekistan Cotton Growing Research Institute, 1981). Depending on the crop development in the treatments, cotton was harvested two to four times as the cotton bolls opened during the harvest period. Raw-cotton subsamples from each harvest were oven dried at 70°C for 24 h, and the moisture data were used for calculation of final seed-lint yields.

Table 4. Percentage of field capacity (F_C) at which irrigation applications were triggered for the three crops and their growth stages.

Crop	Percentage of F_C	The three plant growth periods
	%	
Winter wheat	70	(i) from germination to tillering, Zadoks 00–Zadoks 19†
	75	(ii) from tillering to milk-wax, Zadoks 20–Zadoks 75
	70	(iii) from milk-wax to full grain ripeness, Zadoks 75–Zadoks 92
Maize	70	(i) from germination to 5–6 leaves, VE–V5‡
	75	(ii) from 5–6 leaves to milk-wax, V5–R3
	65	(iii) from milk-wax to full grain ripeness, R3–R6
Cotton	70	(i) from germination to squaring, Stage 0–5§
	70	(ii) from squaring to flowering–fruiting, Stage 5–7
	60	(iii) during maturation of cotton bolls, Stage 7–9

† The stages of development according to Zadoks et al. (1974).
‡ The stages of development according to Ritchie et al. (1986).
§ The stages of development according to Elsner et al. (1979).

Statistics

All data of the split-plot experiment were checked for normality and analyzed with mixed linear model techniques using the MIXED procedure in SAS Version 9.2 (SAS Institute, 2008). This included the variables bulk density, water-stable macroaggregation (WSMA), yield, harvest index (where applicable), plant population, IWUE, and total water use efficiency (WUE). The effects are presented as least square means under multiple comparison protection via the Tukey adjustment. The significance level for comparing differences was set to $P = 0.05$.

The results are presented in accordance with the statistical significance of interaction of the main effects of treatment. For instance, ANOVA showed that tillage × depth was the highest level of interaction for soil ρ_b; hence, this interaction was the only result we present and discuss to evaluate the effects of soil tillage and depth on soil ρ_b.

RESULTS AND DISCUSSION

Soil Bulk Density, Water-Stable Macroaggregation, and Water Infiltration

An ANOVA showed that soil ρ_b was significantly affected by depth ($P = 0.001$), type of tillage ($P = 0.05$), year ($P = 0.001$), and tillage × depth ($P = 0.001$) and depth × year ($P = 0.001$) interactions. Several researchers have reported greater ρ_b for CA than CT systems (Arshad and Gill, 1996; Balesdent et al., 2000; Schwartz et al., 2003; Thomas et al., 2007). Although the topsoil 0- to 0.1-m layer exhibited the lowest ρ_b, the overall effect of residue retention on ρ_b was not pronounced; on average, ρ_b was significantly affected with time for the 0.1- to 0.2- and 0.2- to 0.3-m depth ranges (Table 5). At those depths, ρ_b was always greater for PB than for CT, and significantly so in 2005. Less soil compaction under rotations that included a wheat crop was reported by Hulugalle et al. (2007), but our results are ambivalent in that regard.

During the 4 yr, the PB system slightly but significantly increased ρ_b compared with CT but only for the 0.1- to 0.2- and 0.2- to 0.3-m soil strata (Table 5). The increase in ρ_b for PB over CT was only significant in 2005, however, whereas the observed increasing trends in the other years and soil layers were insignificant. The topsoil

Table 5. Effects of soil tillage and depth on soil bulk density (ρ_b) from 2005 to 2008. Data are for maize in 2005 and 2006. No data were available for winter wheat in the 2005–2006 season.

		ρ_b			
Year	Soil tillage†	0–0.1 m	0.1–0.2 m	0.2–0.3 m	0.3–0.4 m
		Mg m^{-3}			
2005	CT	1.22 Ab‡	1.25 Bb	1.34 Ba	1.36 Ba
	PB	1.22 Ac	1.34 Ab	1.39 Aa	1.42 Aa
2006	CT	1.23 Acb	1.21 Acb	1.32 Aba	1.46 Aa
	PB	1.19 Ab	1.36 Aa	1.41 Aa	1.42 Aa
2007	CT	1.31 Acb	1.29 Acb	1.34 Aba	1.40 Aa
	PB	1.32 Ab	1.37 Aba	1.41 Aa	1.40 Aa
2008	CT	1.32 Ab	1.31 Ab	1.33 Aba	1.38 Aa
	PB	1.32 Ab	1.36 Aba	1.38 Aa	1.41 Aa
2005–2008 avg. (tillage × soil depth)	CT	1.27 Ac	1.27 Bc	1.33 Bb	1.40 Aa
	PB	1.26 Ac	1.36 Ab	1.40 Ab	1.41 Aa

† CT, conventional tillage; PB, permanent beds.

‡ Least square means in a column and for each year followed by the same uppercase letter and least square means in a row across soil depth in each year followed by the same lowercase letter are not significantly different at $P < 0.05$ according to the adjusted Tukey multiple comparison test.

0- to 0.1-m layer exhibited the lowest ρ_b. Soil porosity (ϕ) exhibited similar, but inverse, trends to ρ_b (data not shown).

The total WSMA was not affected by tillage and residue retention but was impacted by year ($P = 0.001$), depth ($P = 0.001$), residue × year ($P = 0.001$), depth × year ($P = 0.01$), tillage × residue × year ($P = 0.001$), tillage × residue × depth ($P = 0.01$), and tillage × residue × depth × year ($P = 0.05$) interactions. There was no clear interaction of WSMA between tillage and depth. Except for the PB+R100 treatment in 2008, during the period 2004 to 2008 and across all depths and soil tillage treatments combined, the WSMA decreased significantly from 40 to 31% under R25 and from 40 to 36% under R100, probably due to the formation of larger aggregates (Table 6). For data combined across years, tillage, and residue retention treatments, the least WSMA occurred in the 0.3- to 0.4-m depth range (data not shown). Studies from Australia have also suggested that structural stability is influenced by tillage and bed systems (Hulugalle and Finlay, 2003).

In 2006 and 2008, water infiltration was not substantially affected by residue retention treatments (Table 7) but only by tillage ($P = 0.05$) and year ($P = 0.001$). The tillage × year interaction was significant ($P = 0.001$). Cotton grown for 2 yr after winter wheat and maize significantly decreased water infiltration in both CT and PB systems regardless of the residue retention practice. For measurements at the end of the maize growing season in 2006, water infiltration was significantly larger in the CT+R100 treatment than in the PB systems (Table 7). The difference between the CT and PB systems was greater in 2008, which probably shows a tillage traffic effect on subsoil compaction that caused increased ρ_b in the PB system (Table 7).

Table 6. Effects of crop residue retention level and year on water-stable macroaggregation (WSMA) at residue retention levels of 25% (R25) or 100% (R100) on a mass basis.

		WSMA	
Soil tillage	Year	R25	R100
		%	
Conventional tillage	2004	40.4 Aa†	40.4 Aa
	2006	33.9 Ba	35.5 ABa
	2008	31.0 Ba	33.1 Ba
Permanent beds	2004	40.4 Aa	40.4 Aa
	2006	40.6 Aa	33.7 Bb
	2008	30.4 Bb	37.6 Aa
Avg. across tillage methods (residue × year)	2004	40.4 Aa	40.4 Aa
	2006	37.2 Aa	34.6 Ba
	2008	30.7 Bb	35.5 Ba

† Least square means in a column within each soil tillage group followed by the same uppercase letter and least square means in a row across crop residue retention levels in each year followed by the same lowercase letter are not significantly different at $P < 0.05$ according to the adjusted Tukey multiple comparison test.

Soil Organic Carbon and Particulate Organic Matter Dynamics

Soil organic C was significantly affected by year ($P = 0.001$) and crop residue retention level ($P = 0.001$) but not impacted by the type of soil tillage. The effects of interactions between crop residue retention level and year ($P = 0.01$) and between soil tillage and crop residue retention level ($P = 0.05$) were significant.

Retention of 100% of the residues of winter wheat and maize grown for two consecutive years in the wheat–maize–cotton sequence had a significant positive effect on SOC in both the CT and PB systems (Table 8). Compared with the initial value in 2004, the SOC increase in 2006 was from 4 to 19% in the 0- to 0.4-m depth. The largest SOC accumulation was observed in the PB+R100 treatment followed by the CT+R100 treatment; the lowest was for the PB+R25 treatment. This occurred despite numerically and sometimes significantly smaller grain and stover yields for the 100% residue retention treatments, and numerically and sometimes significantly smaller grain and

Table 7. Effects of soil tillage and year on water infiltration under conventional tillage (CT) or permanent beds (PB).

		Water infiltration	
Crop residue retention level	Year	CT	PB
%		mm in 6 h	
25	2006	750 Aa†	709 Ab
	2008	569 Ba	447 Bb
100	2006	769 Aa	699 Ab
	2008	575 Ba	445 Bb
Avg. across crop residue retention levels (tillage × year)	2006	760 Aa	704 Ab
	2008	572 Ba	446 Bb

† Least square means in a column within each crop residue retention level followed by the same uppercase letter and least square means in a row across soil tillage systems in each year followed by the same lowercase letter are not significantly different at $P < 0.05$ according to the adjusted Tukey multiple comparison test.

Table 8. Effects of crop residue retention level and year on soil organic C (SOC) stock dynamics in the 0- to 0.4-m depth layer (all layers combined) at residue retention levels of 25% (R25) or 100% (R100) on a mass basis.

Soil tillage	Year	SOC	
		R25	R100
		Mg ha^{-1}	
Conventional	2004	24.2 Aa†	24.2 Ba
	2006	26.1 Aa	27.4 Aa
	2008	25.0 Aa	25.9 ABa
Permanent beds	2004	24.2 Aa	24.2 Ba
	2006	25.2 Ab	28.9 Aa
	2008	25.3 Aa	27.0 Aa
Avg. across tillage methods (residue × year)	2004	24.2 Ba	24.2 Ca
	2006	25.7 Ab	28.2 Aa
	2008	25.2 ABa	26.5 Ba

† Least square means in a column within a soil tillage group followed by the same uppercase letter and least square means in a row across crop residue retention levels in each year followed by the same lowercase letter are not significantly different at $P < 0.05$ according to the adjusted Tukey multiple comparison test.

Table 9. Effects of soil tillage and year on particulate organic matter (POM) stock dynamics in the 0- to 0.4-m depth layer (all layers combined) under conventional tillage (CT) or permanent beds (PB).

Crop residue retention level	Year	POM	
		CT	PB
%		Mg ha^{-1}	
25	2004	4.4 Aa†	4.4 Ba
	2006	4.8 Ab	8.0 Aa
	2008	2.1 Bb	4.0 Ba
100	2004	4.4 Aa	4.4 Ba
	2006	4.4 Ab	7.5 Aa
	2008	2.1 Bb	7.3 Aa
Avg. across crop residue retention levels (tillage × year)	2004	4.4 Aa	4.4 Ca
	2006	4.7 Ab	7.7 Aa
	2008	2.1 Bb	5.7 Ba

† Least square means in a column within each crop residue retention level followed by the same uppercase letter and least square means in rows across soil tillage in each year followed by the same lowercase letter are not significantly different at $P < 0.05$ according to the adjusted Tukey multiple comparison test.

stover yields for the PB treatments, both of which were due to poor crop population and other concomitant factors.

The particulate organic matter (POM_C) was significantly impacted by tillage ($P = 0.01$), year ($P = 0.001$), and tillage × year ($P = 0.001$), residue retention level × year ($P = 0.01$), tillage × residue retention level ($P = 0.05$), and tillage × residue retention level × year ($P = 0.01$) interactions. The POM_C stock attained its maximum under the PB system (Table 9). In the CT systems, less POM_C was stored in the 0- to 0.4-m depth range. Most likely this was because of intensive mechanical soil disturbance, which causes enhanced mineralization of soil organic matter under CT due to better aeration of the surface soil, and because POM_C occluded within aggregates might become exposed to microbial attack after disruption of aggregates (Karbozova-Saljnikov et al., 2004). Thus, 2 and 4 yr after the treatments were established, PB with partial and full residue retention contributed significantly more to POM_C replenishment than did the CT system, regardless of the residue retention practice (Table 9).

Our results generally agree with those of several studies. Unlike soil aggregation, SOC stratification began soon after a conversion from CT to CA practices in studies by Kay and VandenBygaart (2002) and Micucci and Taboada (2006). A greater increase in total C mass in the soil under ZT compared with a CT system was observed in an experiment in Canada, but this was found to be true only after four cropping seasons (Malhi et al., 2006).

Reicosky et al. (1995) stated that CA has the potential to convert many soils from a source to a sink of atmospheric C by sequestration of C in the soil as organic matter. For instance, the average rates of C sequestration in Brazil and Canada were 0.51 and 0.74 Mg ha^{-1} yr^{-1}, respectively, when CA practices were adopted by farmers (Vlek and Tamene, 2009). In our study, the mean SOC increase rate for 4 yr was 0.70 Mg ha^{-1} yr^{-1} in the 0- to 0.4-m depth range for the PB system with all residue retained (PB+R100), while an average annual rate of C sequestration with CT and incorporation of all crop residues produced in the system (CT+R100) was 0.48 Mg ha^{-1} yr^{-1}.

Yields and Plant Density

The maize grain yield obtained in the PB system in 2005 was significantly less than in the CT system but stover yield, while lower under PB than CT, was not significantly so except for the PB+100 treatment (Table 10). Retention of all crop residues significantly depressed yield, even in the CT system. The yield decrease in the R100 treatments of both the PB and CT systems was caused by a combination of reduced plant density, late plant maturity due to delayed development (probably due to cooler soil), and probably limited N availability due to its immobilization. The most important of these, however, was probably plant density because yield (Y, Mg ha^{-1}) was strongly and linearly related to plant density (D_p, 10^3 plants ha^{-1}) ($Y = 0.039D_p - 0.48$, $r^2 = 0.95$).

Wheat grain and stover yield differences among all treatments of the CT and PB systems were not significant (Table 10), but yield was strongly and linearly related to plant density ($Y = 0.006D_p + 0.82$, $r^2 = 0.88$). It appeared that wheat emergence was better under greater residue amounts. Govaerts et al. (2005) demonstrated significant yield differences due to residue retention rates in wheat under rainfed conditions in Mexico during the initial 4 yr of ZT with crop rotation. The least yields were achieved with no crop residue retained and were nearly 37% less than for full residue retention. A 3-yr field study conducted by Gangwar et al. (2006) in the Indo-Gangetic Plains showed that the best wheat yield was obtained under reduced tillage (5.1 Mg ha^{-1}), followed closely by ZT (4.75 Mg ha^{-1}), compared with CT (4.6 Mg ha^{-1}). The reasons for the greater yields under reduced tillage as stated by these researchers were good aeration, better germination, more water penetration, less weed infestation, and increased nutrition compared with the other systems.

In 2006, the maize yield substantially increased in both tillage systems, particularly in PB, compared with 2005 (Table 10). Besides other concomitant factors, the higher yield in PB was due to an improved crop population in the system. The grain yield for PB+R25 was statistically similar to that for CT+R100, whereas the yield was greater than these for CT+R25 and less than these for the PB+R100 treatment. Similar to the results for maize in 2005, a poorer plant stand in 2006 for the PB+R25 and PB+R100 treatments compared with CT+R25 was one of the reasons for grain and stover yield differences among treatments. Indeed, yield was again strongly and linearly related to plant density ($Y = 0.106D_p - 3.02$, $r^2 = 0.95$). Separate effects of soil tillage method and residue management were significant for both grain yield and stover yield.

Table 10. Least square means of yield and plant density of winter wheat and maize crops in rotation as affected by soil tillage (CT, conventional tillage; PB, permanent beds) and crop residue retention level (R100, 100% residue retention on a mass basis; R25, 25% residue retention on a mass basis).

Crop and Season	Treatment	Dry weight Grain	Stover	Plant density
		— Mg ha^{-1} —		1000 plants ha^{-1}
Winter wheat, 2004–2005	PB+R25	6.20	6.00	363†
Maize, 2005	CT+R25	1.81 A‡	4.17 A	59.4 A
	CT+R100	1.39 B	3.27 BA	46.1 B
	PB+R25	0.99 C	2.31 BC	41.7 C
	PB+R100	0.76 D	1.70 C	31.1 D
Winter wheat, 2005–2006	CT+R25	2.88 A	2.43 A	366† A
	CT+R100	3.15 A	2.23 A	380† A
	PB+R25	2.36 A	1.94 A	260† A
	PB+R100	3.02 A	1.84 A	341† A
Maize, 2006	CT+R25	2.87A	7.74 A	55.2 A
	CT+R100	2.22 B	6.16 B	50.6 BA
	PB+R25	2.00 B	5.25 BC	45.8 BC
	PB+R100	1.41 C	4.58 C	42.5 C

† Total number of culms (spikes m^{-2}).

‡ Least square means in columns within each crop followed by the same uppercase letter are not significantly different at $P < 0.05$ according to the adjusted Tukey multiple comparison test.

Table 11. Least square means of yield, harvest index, and plant density of cotton as affected by soil tillage (CT, conventional tillage; PB, permanent beds), and crop residue retention level (R100, 100% residue retention on a mass basis; R25, 25% residue retention on a mass basis).

Year	Treatment	Seed-lint yield	Harvest index	Plant density
		Mg ha^{-1}		1000 plants ha^{-1}
2007	CT+R25	2.89 BA†	0.34 A	62.8 A
	CT+R100	3.13 A	0.34 A	67.5 A
	PB+R25	2.13 B	0.34 A	51.5 B
	PB+R100	1.37 C	0.33 A	49.9 B
2008	CT+R25	2.71 B	0.43 A	61.2 A
	CT+R100	3.21 A	0.45 A	62.5 A
	PB+R25	2.24 C	0.45 A	60.9 A
	PB+R100	2.51 BC	0.45 A	60.3 A

† Least square means in columns in each year followed by the same uppercase letter are not significantly different at $P < 0.05$ according to the adjusted Tukey multiple comparison test.

Irrigated cotton plant density was significantly less in the PB system in 2007 but not in 2008, while the effects of residue retention were mixed (Table 11). Poor germination of cotton seeds planted in April 2007 in the PB system probably was caused by a lower soil temperature, which adversely affected emergence (Mahan and Gitz, 2007; Dong et al., 2008). Cold soils begin to impact germination when temperatures decrease to 15.5°C (Boman and Leman, 2005). The measured diurnal temperature at the 5-cm soil depth during germination for the PB+R100 treatment was 1.3 to 4.0°C less than for CT+R100 (Fig. 1). Hence, poor stand establishment due to less germination was also a cause of diminished seed-lint yield, with the penalty ranging from 0.8 to 1.8 Mg ha^{-1} for the PB system compared with CT in 2007. In 2008, the yield differences between the CT and PB systems at the same residue retention level were again significant, averaging 1.17 Mg ha^{-1}. The effect of tillage method was significant in both 2007 and 2008. The effect of residue retention level was significant only for the PB system in 2007 and the CT system in 2008 (Table 11). The reduction of maize and cotton plant populations observed in the PB system in 2005–2006 was overcome in 2008 due to better weather conditions and a better handling of the agricultural equipment. The harvest index also was considerably improved, from 0.33 to 0.34 in 2007 to 0.43 to 0.45 in 2008 ($P < 0.0001$, analysis not shown).

Similar to our findings, Govaerts et al. (2009) concluded that findings for CA treatments did not always point in the same direction. This contrasted with the findings of Derpsch (2008), who concluded that generally similar and even yields were achieved with no-till compared with CT systems, at least when farmers had experience with CA, including with the regulation of the seeder–planter, N fertilization management, and the use of appropriate crop rotations; the results of Malhi et al. (2006) in Canada were similar. In another 4-yr experiment in Uzbekistan, cotton yield under an irrigated PB system and full residue retention significantly decreased in the first year. But in the third year of that experiment, the PB yields were comparable to those of CT because in the third year residues were sufficiently applied (Tursunov, 2009). Adverse effects on yield of a ZT system in Iran were linked to fine-textured soil and low SOC (Hemmat and Taki, 2001). Correa and Sharma (2004) found that improvements in soil quality, cotton yield, and profitability with CA were greater when cotton was rotated with cereal crops than when rotated with legumes; Naderman et al. (2004) found the greatest improvements with a cotton–cereal–legume sequence in which the legume was a winter cover crop. The improved yields for CT when residue retention was increased in our experiment point to improved water conservation. The inconsistent results vis-à-vis residue retention with PB indicate that cooler soils resulting from increased residue may require changes in tillage practices, such as strip tillage before planting, to allow soil warming in the seedbed. To avoid immature maize harvest at the R3 to R5 growth stages, it is also possible to plant shorter maturity maize hybrids, which exist and are used by farmers in Uzbekistan, such as the cultivars Moldova 215MB (FAO 190) or Moldova 257AMB (FAO 210).

Crop Water Use and Irrigation Water Use Efficiency

Both tillage and year significantly affected WUE and IWUE, although tillage × year ($P = 0.001$) and residue retention rate × year ($P = 0.01$) interactions were only significant for WUE. The amount of irrigation water applied during the maize vegetative season in 2005 varied from 362 to 374 mm among treatments in concert with crop water use (ET) values that ranged from 408 to 454 mm (Table 12), while precipitation was only 8 mm (data not shown). These short-season (July–October) maize ET values were about 23% smaller in this dry year than values ranging from 497 to 578 mm for long-duration (April–September) irrigated maize grown under CT and furrow irrigation at Tashkent, Uzbekistan (Ibragimov et al., 2005). Decreased yield of maize with PB treatments resulted in significantly decreased WUE and IWUE values compared with CT (Table 12). The IWUE attained its maximum (0.50 kg m^{-3}) for the CT+R25 treatment, which was 32% greater than for CT+R100 (Table 12). In 2006, precipitation was 50 mm, but maize water use followed the same treatment order as in 2005. Irrigation ranged from 363 to 390

Table 12. Impact of tillage (CT, conventional tillage; PB, permanent beds) and crop residue retention level (R100, 100% residue retention on a mass basis; R25, 25% residue retention on a mass basis) on seasonal treatment-mean water use (evapotranspiration, ET), irrigation water use efficiency (IWUE), and overall water use efficiency (WUE) of maize, winter wheat, and cotton.

Crop and season	Parameter	Treatment mean			
		CT+R25	CT+R100	PB+R25	PB+R100
Maize, 2005	ET, mm	416	408	424	428
	IWUE, kg m^{-3}	0.50 a†	0.38 b	0.26 c	0.20 d
	WUE, kg m^{-3}	0.44 a	0.34 b	0.23 c	0.18 d
Winter wheat, 2005–2006	ET, mm	717	728	719	715
	IWUE, kg m^{-3}	0.90 a	0.99 a	0.76 a	0.98 a
	WUE, kg m^{-3}	0.40 a	0.43 a	0.33 a	0.42 a
Maize, 2006	ET, mm	375	356	407	402
	IWUE, kg m^{-3}	0.77 a	0.61 b	0.51 b	0.36 c
	WUE, kg m^{-3}	0.77 a	0.62 b	0.49 b	0.35 c
Cotton, 2007	ET, mm	398	402	444	402
	IWUE, kg m^{-3}	0.85 a	0.91 a	0.58 b	0.41 b
	WUE, kg m^{-3}	0.73 a	0.78 a	0.48 b	0.34 b
Cotton, 2008	ET, mm	441	438	487	442
	IWUE, kg m^{-3}	0.64 b	0.76 a	0.48 c	0.59 b
	WUE, kg m^{-3}	0.61 b	0.73 a	0.46 c	0.57 b

† Least square means in rows within parameters for each crop followed by the same lowercase letter are not significantly different at $P < 0.05$ according to the adjusted Tukey multiple comparison test.

mm and ET ranged in concert from 356 to 407 mm (data not shown). Both WUE and IWUE were significantly smaller for the PB+R100 treatment compared with CT+R100 and for the PB+R25 treatment compared with CT+R25, and the order of WUE and IWUE values was the same as in 2005, namely PB+R100 < PB+R25 < CT+R100 < CT+R25.

Irrigation water applied during the 2005–2006 winter wheat growing season ranged from 310 to 320 mm, and the crop received 402 mm of precipitation during the growing season, mainly in the winter months (data not shown). Differences in ET among the CT and PB treatments were negligible, and ET values ranged from 715 to 728 mm. Previously reported ET values for irrigated winter wheat grown under the same conditions were 426 to 492 mm (Kamilov et al., 2002). Our values, however, are more in line with those reported by Schneider and Howell (2001) for irrigation at 75% of full ET under a similar continental climate in the U.S. Southern High Plains. Retention of all residue did not substantially affect ET for all tillage practices. The IWUE values ranged from 0.76 to 0.99 kg m^{-3}, although neither the IWUE nor the WUE differences among treatments were statistically significant (Table 12). Alizadeh and Keshavarz (2005) stated that a reasonable level of IWUE for wheat is about 1.0 kg m^{-3}, which is close to the values for all treatments in this study except for the PB+R25 treatment. Schneider and Howell (2001) reported WUE values ranging from 0.82 to 0.93 kg m^{-3} and IWUE values from 1.14 to 1.46 kg m^{-3} using sprinklers and lower energy precision application (LEPA) irrigation systems at Bushland, TX, considerably greater than the values reported here and perhaps indicating greater efficiency for pressurized irrigation systems. For example, winter wheat grown under furrow irrigation at Bushland averaged a total WUE of 0.77 kg m^{-3} with values ranging from 0.6 to 1.15 (Musick et al., 1994, 178 crop seasons), closer to the values reported here.

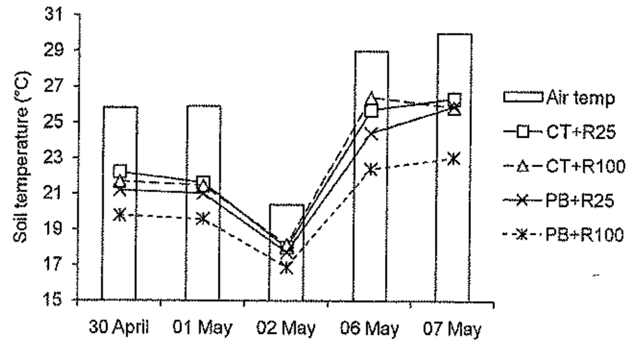

Fig. 1. Average diurnal temperature at the 5-cm soil depth during germination of cotton in 2007 under conventional tillage (CT) or permanent beds (PB) with residue retention levels of 25% (R25) or 100% (R100) on a mass basis.

In 2007, cotton irrigation ranged from 333 to 368 mm, while ET ranged from 398 to 444 mm and precipitation was 46 mm (data not shown). In 2008, cotton irrigation ranged from 421 to 470 mm while ET ranged from 438 to 487 mm and precipitation was 45 mm but less well distributed than in 2007 (data not shown). The IWUE and WUE values for cotton grown in 2007 were larger under CT than PB (Table 12), which could be explained by stunted plants at the onset of the vegetation season and a lower crop population in the PB treatments. The cotton IWUE in 2008 for the PB+R100 treatment was larger at 0.59 kg m^{-3}, which is comparable to values ranging from 0.55 to 0.62 kg m^{-3} for a 3-yr study of conventionally tilled and furrow-irrigated cotton under similar conditions in Uzbekistan (Ibragimov et al., 2007). The WUE and IWUE values for both PB treatments were significantly smaller than values for the CT treatments in 2007. In 2008, the largest IWUE occurred with the CT+R100 treatment. Except for the stunted cotton in 2007, increased residue retention (R100) had a positive effect on winter wheat and cotton WUE and IWUE values, often significantly, regardless of tillage treatment (Table 12), a likely result of a reduction in evaporative losses. The opposite was true for maize in 2005 and 2006. This inability of CA practices to consistently improve WUE or IWUE requires further investigation. For instance, to fully understand the transpiration stream and the effects of CA on crop development and water use requires a combination of measurement and separation of the evaporation (E) and transpiration (T) components of crop water use (ET), with numerical modeling of crop development and the energy and water balance of the crop.

SUMMARY

In contrast to the many research reports from rainfed areas, less information is available about CA practices under irrigation (Sayre and Hobbs, 2004). Four years after establishment of our CA practices, our crop rotation and sequence experiment (irrigated winter wheat–maize–cotton) showed improvement of soil physical properties and SOC concentration under PB with all residue retained (R100). The benefits of CA only began to become evident in the fourth and final year of the study. Winter wheat grown in rotation and its residues had a positive impact on ρ_b in both CT and PB systems, while cotton cropping resulted in increased soil compaction. In general, for the PB+R100 treatment, the SOC increase rate during the first 4 yr of the study was 0.70 Mg ha^{-1} yr^{-1}, compared with a rate of 0.48 Mg ha^{-1} yr^{-1} for

CT and incorporation of all crop residues. For cotton in 2007 and maize in 2006, cool and wet soil conditions in the PB systems resulted in stunted plants at the beginning of the vegetation season and lower plant populations, which caused smaller WUE and IWUE values. We believe that the improvement of cotton yields in 2008 vs. those in 2007 under CA was partly linked to both the improved soil conditions and improved management of the crops grown using the new practice of CA in Uzbekistan; however, the fact that the CT+R25 treatment yielded less in 2008 than in 2007 while the CT+R100 treatment yielded more in 2008, coupled with the greatly increased yield of the PB+R100 treatment in 2008 over that in 2007, indicates that evaporative demand was greater in 2008, causing the greater residue retention in R100 to be an important and effective component of CA. Although crop yields may be reduced with CA, the reduced cost of production is the main driving force for a transition to CA (Tursunov, 2009). There is good potential for production cost reductions to be balanced against reduced income from crop yields. Training and multiyear support of farmers as well as appropriate tillage, harvesting, and planting equipment will be needed if a transition to CA is to be successful in Central Asia.

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