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Combining permanent beds and residue retention with nitrogen fertilization improves crop yields and water productivity in irrigated arid lands under cotton, wheat and maize

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ABSTRACT

Intensive soil tillage and mismanagement of irrigation water and fertilizers are increasing production costs, reducing soil fertility and crop water productivity and threatening the sustainability of crop production systems in the irrigated arid lands of Uzbekistan, Central Asia. Conservation agriculture (CA) practices combined with optimum nitrogen (N) management can counterbalance some of these adverse effects. Most work has been done in rainfed areas so there is less information available for irrigated production systems. This study compared the effects of tillage, crop residue management and N rates on yield and water productivity for irrigated cotton, winter wheat and maize grown in a two-year rotational sequence in Uzbekistan under CA practices vs. current conventional farmer practices. Permanently raised beds (PB) and conventional tillage (CT) were compared under two crop residue levels (retained residue – RR and removed residue – RH), and three N levels (zero, medium and high, with actual rates depending on the crops) on a sandy loam to loam soil. Raw cotton yield, yield components and water productivity were not affected by tillage methods. However, the following crops, wheat and maize, produced 12 and 42% higher grain yields, respectively, under PB than under CT. Under PB, water productivity increased in wheat by 27% and in maize by 84%, while 11% less water was applied during wheat and 23% during maize production, compared to CT. All three crops showed a considerable increment in yield and water productivity when N fertilizer levels were increased from zero to medium N application, and a relatively much lower increment when the N rate was doubled from medium to high N, for both tillage methods. In maize, the response to applied N was more pronounced with PB than with CT. Irrespective of tillage method, RR increased the grain yield of wheat by 5% compared to RH. In maize, RR in PB increased grain yields by 15% compared to RH. RR had no effect for CT. The positive effect of PB and RR on yield and water productivity of wheat and maize and the lack of negative effects on cotton yield reflect that PB with RR and proper N application may be viable alternatives to the present, unsustainable conventional agriculture practices in these irrigated arid lands, assuming the patterns are confirmed in the long-run.

1. Introduction

Irrigated agriculture provides about 40% of the global agricultural production from just 20% of the total cultivated land. However, FAO (2002) predicted that the irrigated areas will need to expand from 202 million ha (Mha) in 1999 to 242 Mha by 2030 to meet the food demands of the growing population in developing countries. Irrigation water is particularly important in arid climates, where potential evapotranspiration exceeds precipitation. Central Asia is over 80% arid and it is most important that agricultural production is done in a sustainable manner for food security, employment, livelihoods and environmental protection. Cotton, wheat and maize are the major commercial and food crops grown in the five Central Asian countries, i.e., Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan (FAOSTAT, 2010), often as mono-cultures on large areas using conventional tillage and irrigation via flood and furrows. Conventional tillage (CT) involves intensive land preparation with up to 4–5 machinery passes, and

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often needs deep tillage to reduce soil compaction caused by heavy machinery. In addition, poorly managed flood irrigation and dysfunctional drains combined with the excessive use of chemical inputs are typical of the conventional land use practices. The recommended N rates for cotton or wheat is 160–180 kg N ha^{-1} and 150 kg N ha^{-1} for short-duration maize (MAWR, 2000). Previous research has shown that these rates, determined decades ago, need to be adjusted (Kienzler, 2010). Previous findings confirmed a rather low nitrogen (N) use efficiency of 33% (Kienzler, 2010) which is far less than the 50–80% reported in well managed field experiments for both low and upland crops (Cassman et al., 1993; Dobermann et al., 2000; Cassman et al., 2002). The wasteful use of resources like irrigation water and chemical fertilizers is polluting the environment (Scheer et al., 2008), increasing production costs, raising the groundwater level which increases secondary soil salinization (Forkutsa et al., 2009), deteriorating soil quality, and thus threatening the sustainability of the overall crop production system in the irrigated arid lands of Central Asia.

Conservation agriculture (CA) principles that imply reduced tillage, proper crop rotation, and retention of optimal levels of crop residues have been adopted by farmers on more than 100 Mha world wide as of 2008 (Derpsch and Friedrich, 2009). CA is predominantly practiced in North and South America, Australia, and other semi-arid areas of the world (Holland, 2004) but less widely introduced in the world's irrigated areas. Among the various CA practices, reduced tillage is predominating worldwide (Yau et al., 2010). Reduced tillage technologies effectively minimize soil disturbance, reduce evaporation from soils, enhance soil carbon sequestration, and reduce energy needs, thus lowering production costs (Lal et al., 2007).

The use of permanently raised beds (PBs), a reduced tillage practice, is gaining adoption in different crop production systems. Previous studies have shown that PB with residue retention has an advantage over zero-till flat (ZT) and CT (Limon-Ortega et al., 2000; Sayre and Hobbs, 2004; Tursunov, 2009). The benefits include higher irrigation water use efficiency (Sayre and Hobbs, 2004; Hassan et al., 2005), better plant establishment (Khaleque et al., 2008; Gürsoy et al., 2010), lower production costs (Gupta et al., 2009; Tursunov, 2009; Hari-Ram et al., 2012), and with equal or higher crop yield (Sayre and Hobbs, 2004; Govaerts et al., 2005; Boulal et al., 2012). Crop production on PB is 9% more energy-efficient than under ZT, 12% more efficient compared to freshly prepared beds and even 19% more efficient than conventional practices (Rautaray, 2005), while the cultivation costs can be reduced by one-third with PB in Central Asia (Gupta et al., 2009). Furthermore, PBs also increase grain yield and water use efficiency in irrigated cotton (Boulal et al., 2012), wheat and maize (Harris and Krishna, 1989; McFarland et al., 1991; Sayre and Hobbs, 2004; Wang et al., 2004; Hassan et al., 2005; Gupta et al., 2009).

A major challenge for sustainable agriculture production on irrigated croplands in Central Asia is to increase water productivity which has been falling for decades due to high water application rate (Abdullaev and Molden, 2004). The average water productivity of cotton in the Syr Darya basin is ~0.37 kg m^{-3}, much below the world average 0.60 kg m^{-3} (Abdullaev and Molden, 2004). Several studies showed the potential of PBs to increase crop water productivity by 25–40% in irrigated agriculture (Sayre and Hobbs, 2004; Hassan et al., 2005; Akbar et al., 2007).

Reduce tillage is especially effective when combined with a surface mulch of crop residues (Lal et al., 2007) which helps to reduced evaporative water loss and increase the soil's water retention capacity (Gant et al., 1992). However, N response in reduced tillage with and without residue retention may differ. For example, in some cases, at the onset of the conversion to conservation tillage, N fertilizer rates need to be increased by about 25% to counteract the yield-reducing effect of short-term N immobilization (Randall and Bandel, 1991; Wienhold et al., 1999). However, in some cases this increase is not necessary; as the soil mineral N distribution in the top soil is altered (Franzluebbers et al., 1995; Angas et al., 2006) and the availability of N improves in a few years (Rice et al., 1986). Similarly, Torbert and Reeves (1994) also concluded that in the long-run N applications can be reduced under reduced tillage practices due to an increase in N uptake efficiencies caused by reduced soil traffic.

The advantages of conservation over conventional practices have been repeatedly shown for rainfed conditions (Lopez-Bellido et al., 1996; DeVita et al., 2007), and also more recently under irrigated conditions (Gupta et al., 2009; Pulatov et al., 2011; Verhulst et al., 2011a; Boulal et al., 2012; Naresh et al., 2012). In the irrigated drylands of Central Asia, the effects of N application, under CA practices on crop performance, production and water productivity of major crops such as cotton, wheat and maize are still poorly understood (Gupta et al., 2009; Pulatov et al., 2011). Based on earlier work, we theorize that combining permanent beds with residue retention and proper nitrogen application can improve crop yield and water productivity relative to the conventional agriculture practices in irrigated arid-lands. Thus, yield and water productivity of cotton, wheat and maize grown in sequence under CA practice were compared to conventional practices with various amounts of N fertilizer applied.

2. Materials and methods

2.1. Site description

In October 2007, a long-term experiment on a cotton–wheat-third crop rotation was started in western Uzbekistan (41°32′12″ N, 60°40′44″ E, and 100 m a.s.l.). The experimental field of 3.1 ha had been mono-cropped for 20 years with cotton under heavy mechanization. The field had received annual fertilizer applications in the order of 200:140:100 kg NPK ha^{-1}. The studied rotational cycle lasted from May 2008 to October 2009. Field preparations consisted of deep ploughing, laser-guided land leveling and salt leaching in October/November 2007 and March 2008. Cotton was sown in May 2008 and harvested in October 2008. The experiment on the impact of tillage, N and residue level was initiated after this, in the sequence of winter wheat (October 2008–June 2009) and maize (June–October, 2009).

The soil in the experimental area is an irrigated alluvial meadow, with sandy loam to loam texture, low in organic matter (0.3–0.6%) and was saline (2–12 dS m^{-1}). The groundwater table in the area is generally shallow (0.5–2 m). The climate is arid, with long, hot and dry summers and short, very cold winters. Average precipitation is less than 100 mm $year^{-1}$ and potential evaporation always greatly exceeds total precipitation. During the experiment cotton, wheat and maize received 14.6 mm, 72.6 mm, and 35.4 mm of rainfall, respectively. In the wheat season 71% of the total rain falls during winter (November–March). In the maize season all rainfall was concentrated in mid September, i.e., during crop maturity.

2.2. Experimental design, treatments and crop management

The experiment was conducted as a randomized complete block with four replications involving two tillage treatments as main plots (permanent bed (PB) and conventional tillage (CT)) and a factorial combination of two residue levels (previous crop residue retained: RR or residue harvested/removed: RH) and three N levels (0, medium and high) as subplots. The medium N level was 125 kg N ha^{-1} for cotton and 100 kg N ha^{-1} for wheat and maize, and the high N level was 250 kg N ha^{-1} for cotton and 200 kg N ha^{-1} for wheat and maize. The experimental subplots were 550 m^2 (11 m × 50 m).