Research Article

Improved Soil Physical Properties, Yield and Water Productivity under Controlled Traffic, Raised-Bed Farming

Ghani Akbar[1*], Muhammad Munir Ahmad[1], Muhammad Asif[1], Iqbal Hassan[2], Qurban Hussain[3] and Greg Hamilton[4]

[1]Climate Change, Alternate Energy and Water Resources Institute (CAEWRI), National Agricultural Research Centre (NARC), Park Road, Chak Shahzad, Islamabad; [2]Professional Agricultural Engineer, former Senior Scientist of CAEWRI-NARC; [3]Natural Resources Division, Pakistan Agricultural Research Council (PARC), Islamabad; [4]Maximum Soil and Water Productivity Pty Ltd. Perth WA, Australia.

Abstract | Excessive irrigation application and intensive tillage is the norm on Pakistani farms, which exacerbate water logging and salinity and reduce the water productivity of major crops. Addressing these issues, a long term experiment (2000 to 2009) under wheat-maize (9 seasons each) cropping pattern was conducted on raised beds (with furrow spacing of 65 cm (Narrow Bed-NB), 130 cm (Medium Bed- MB) and 180 cm (Wide Bed-WB)), with controlled traffic regime emplaced, in comparison with traditional intensive cultivated flat basin (FB) for evaluating impacts on soil, crop and water productivity. The results showed reduced bulk density by 7%, 6% and 5% and increased hydraulic conductivity by 90%, 106% and 72% for WB, MB and NB respectively, when compared with FB. The irrigation water saving was 36%, 40% on WB, 34%, 31% on MB and 7%, 8% on NB, for wheat and maize crops respectively, when compared with FB. The crop yields were higher by 14%, 25% on WB, 12%, 10% on MB and 3%, 13% on NB, respectively, compared with FB. Consequently, the water productivity was also increased by 43%, 71% on WB, 30%, 30% on MB and 4%, 18% on NB for wheat and maize crops respectively. This study have shown the prospects of improved soil physical properties and water productivity by adopting controlled traffic raised bed farming (CTRBF) system, which may be helpful for agriculture sustainability and food security.

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Correspondence | Dr Ghani Akbar, Climate Change, Alternate Energy and Water Resources Institute (CAEWRI), National Agricultural Research Centre (NARC), Park Road, Chak Shahzad, Islamabad; **Email:** ghani_akbar@hotmail.com
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Introduction

The global agriculture sector, in general, and Pakistan in particular, are under increasing pressure to sustainably produce more grain with less input, due to increasing population, declining land and water productivity potential (McGarry, 2003) and increasing cost of production (Tullberg et al., 2007). The traditional flat basin irrigation system with intensive tillage is not sustainable because it causes excessive water losses (Kalwij, 1997), exacerbate water logging and salinity (Qureshi et al., 2008) and degrade soil physical properties (Hassan et al., 2005). It has been shown that the raised bed farming system can combine most elements of conservation agriculture and has the potential of sustainable crop production under various environmental conditions throughout the world. Raised bed with controlled traffic has been shown to reduce field compaction and restore the physically degraded Vertisol soil structure (McHugh

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et al., 2009) in Queensland, Australia. Raised bed have also been shown to save irrigation water and increase crop yield (Kahlown et al., 1998; Ahmad et al., 2009) while reducing the risk of water logging and salinity (Hamilton et al., 2005; Bakker et al., 2010). Raised beds offer the opportunity to reduce tillage, which may reduce land preparation costs according to (Limon-Ortega et al., 2006), because of the reduced machinery field operation time. Raised bed can also facilitate crop residue retention (Li et al., 2001; Wang et al., 2012), mitigate weed infestation (Hulugalle and Daniells, 2005) and provide better mid-season field access for weeding, spraying, fertilizing, irrigating and harvesting operations. However, majority of these techniques are not properly adopted in Pakistan, thus consequently the Indus Basin Irrigation System is operating at less than 60% application efficiency (World Bank, 1997).

Different raised bed sizes are used throughout the world depending mainly on the soil type, available machinery and local expertise. Increasing the width of the bed reduces total water use, increase land use efficiency and enhance yield per unit cultivated area by reducing the un-cropped furrow area (Jin et al., 2007). In Australia, raised bed widths of 2 to 3 m are common while 0.6 to 1.5 m widths is common in China, Pakistan, India and Bangladesh (Sayre and Hobbs, 2004). Wide beds under the rigid medium loam soils with non-shrinking swelling properties and a history of intensive tillage in Pakistan may affect raised bed performance due to slow lateral wetting into the centre of wide beds (Akbar et al., 2015). Although, raised beds have been widely adopted for row crops in Pakistan, but adoption of best management practices for improving soil physical properties and increasing water productivity on sustainable basis is still in its infancy in Pakistan.

Addressing these issues this study was conducted to examine the effect of different sizes of controlled traffic raised beds on soil properties, crop yield and water productivity in comparison with traditional intensively cultivated flat basin system under wheat maize cropping pattern.

Material and Methods

Site Descriptions

The study area is located at Mardan district of Khyber Pakhtunkhwa (KPK) province of Pakistan, at 34°12″E latitude and 73°03″N longitude (Figure 1). It falls in the semiarid zone for both summer and winter seasons with mean seasonal rainfall of 250 mm in summer (May-September) and 300 mm during winter (October-April). The soil at the site is sandy clay loam, that belongs to the Mardan soil series classified as fine Ustertic Camborthid developed in filled basinand river bed, grayish brown, non to slightly calcareous material of Holocene age (Shafiq et al., 2002).

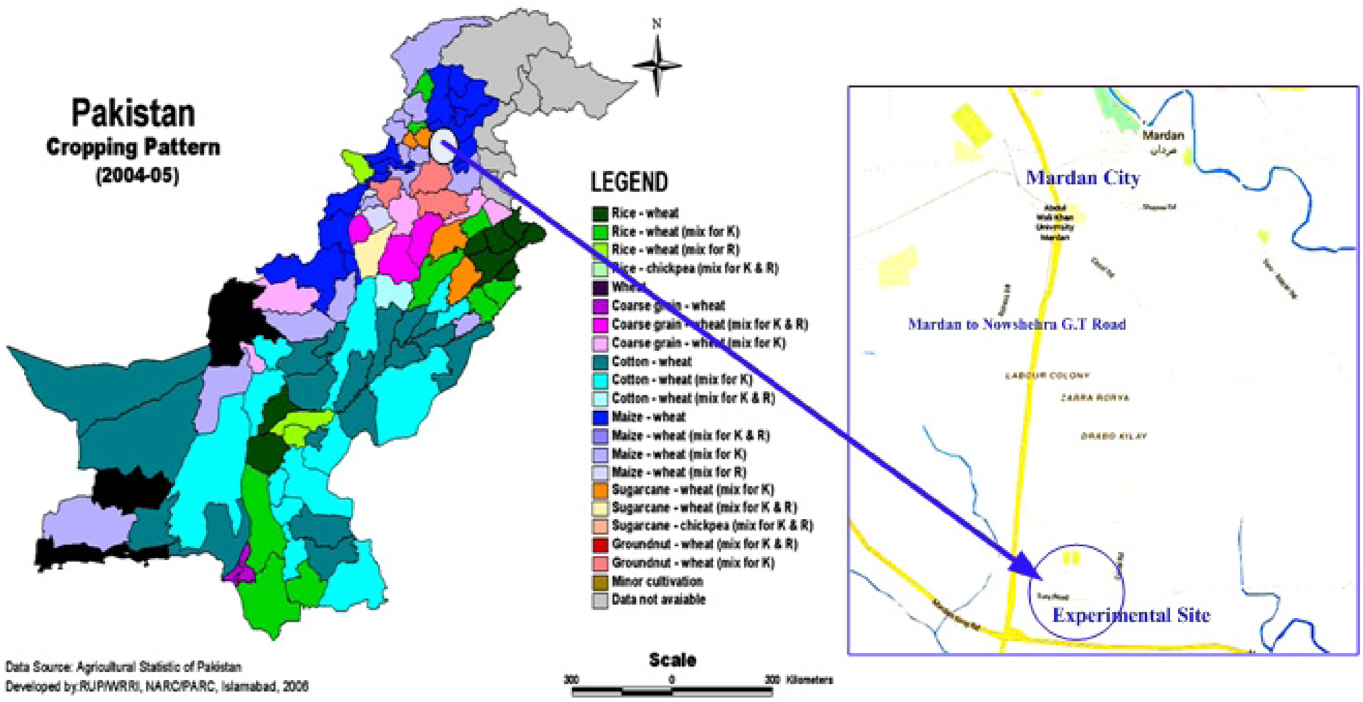

Figure 1: *Location map of site with map of Pakistan showing cropping pattern (Source of cropping pattern map is CAEWRI-NARC Islamabad 2005)*

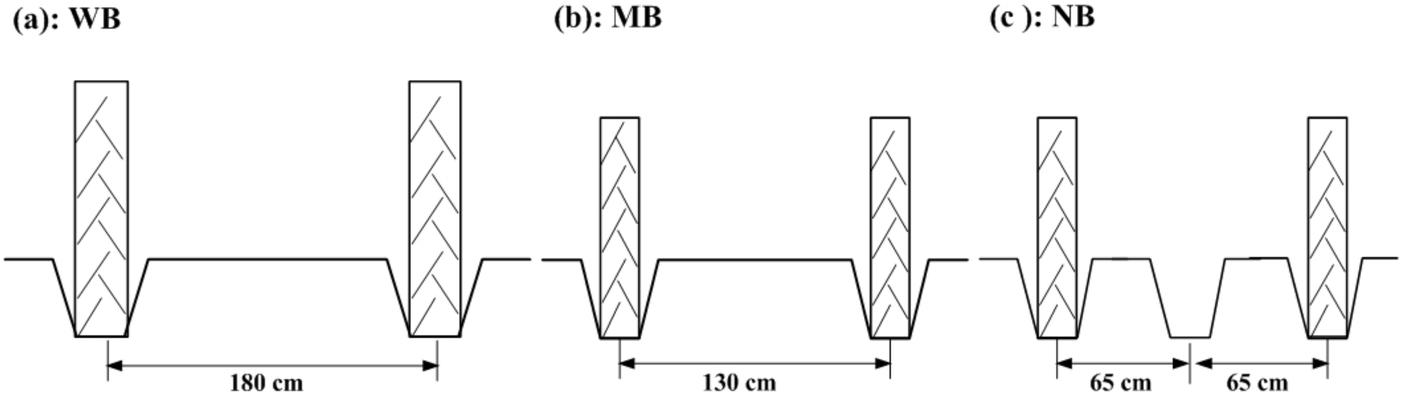

Figure 2: *Controlled traffic raised bed treatments with WB emplaced during experiment 1 (2000-2004) and MB and NB emplaced during experiment 2 (2005-2009) under maize wheat cropping pattern*

This site is under wheat maize cropping since more than a decade at the commencement of the experiment. Wheat and maize crops planting in November and June respectively, on flat basin, after deep tillage, shallow cultivation and rotary hoeing in sequence is the general practice at this experimental plot, before imposing the experimental treatments.

Experimental Treatments

The experiment comprised of evaluating three bed sizes including wide bed with 180 cm furrow spacing (WB), medium bed with 130 cm furrow spacing (MB) and narrow bed with 65 cm furrow spacing (NB) in comparison with flat basin (FB) as shown in Figure 2. The furrow positions for all raised beds treatments were kept permanent throughout the experimental periods and the beds were furrow cleaned only, after shallow cultivation on beds. Soil compaction on bed was minimized by controlling the field machinery traffic to furrows only, by matching tractor track width with furrow spacing. The track width FIAT 370 (75 hp) matched the WB size and MF 260 (50 hp) track width matched the MB and NB treatments.

The routine farmer practice was emplaced for FB treatment, with deep cultivation followed by shallow cultivation and finally rotary hoeing. The experiment was conducted in two phases, with experiment 1 during (2000-2004), which was focused on WB Vs FB comparisons and experiment 2 during (2005-2009), which was focused on MB and NB Vs FB comparisons. Wheat maize cropping pattern was followed during both experimental periods. For wheat crop the WB, MB and NB accommodated seven, five and two crop rows at 20 cm spacing, respectively. For maize crop two crop rows were planted to the edge of WB and MB and a single row to the middle of NB treatment. A completely randomized block design was followed with three replications for each treatment during both experiments. All inputs including seed rate, fertilizers, pesticides and herbicides were equally applied to all treatments.

Data collection and analysis

Soil Moisture and Bulk Density: The soil moisture and bulk density were determined gravimetrically for 0-100 cm profile depth at 10 cm depth intervals, sampled at bed middle and edge covering field head, middle and tail section for all treatments. These samples were collected at sowing, before and after each irrigation and at crop harvest. The soil samples of known volume (98.214 cm^3) were oven dried for 24 hours at 105°C after recording its wet weight. The soil moisture content was determined according to equation 1 (William and Whitman, 1969):

$$\theta_m = M_w \times M_d^{-1} \times 100 \qquad (1)$$

Where;
θ_m = Soil moisture content on dry mass basis in %
M_w = Mass of water within the soil sample (g)
M_d = Mass of dry soil (g)

The soil bulk density ρ_b (g cm^{-3}) was calculated by dividing the dry soil mass (g) with the sample volume (98.214 cm^3) according to equation 2:

$$\rho_b = M_d \times V_b^{-1} \qquad (2)$$

Where;
ρ_b = Bulk Density (gm cm^{-3})
M_d = Mass of dry soil (gm)
V_b = Bulk volume of soil sample (cm^3)

The volumetric soil moisture θ_v in (mm) per specific soil layer depth was calculated by multiplying the gravimetric soil moisture with soil layer depth and its bulk density. The calculation are as per following

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equation 3 (Dingman, 2002):

$$\theta_v = \theta_m \times \rho_b \times d \qquad (3)$$

Where;

θ_v = Volumetric soil moisture (cm)

d = depth of soil layer sampled (cm)

Irrigation Applications: Irrigation was planned after 65% of total available soil water depletion in the root zone of all treatments, but the fixed turn system under canal warabandi system in the experimental area compelled for slight variations. Irrigation cutoff time was managed to fulfill the irrigation requirement, determined through soil moisture gravimetric sampling prior to each irrigation, which generally practically matched to cut-off irrigation at arrival of wetting front to tail end of the field in FB and NB treatments and filling of furrows with slight overtopping in MB and little longer overtopping period for WB treatments. Irrigation application was measured with cut throat flume and real time calculations were done manually for applying the required irrigation depth. Wetting front movement into the centre of WB and MB was visually observed during each irrigation event. Irrigation time was determined as per equation 4:

$$T = A \times D \times Q^{-1} \qquad (4)$$

Where;

T = Irrigation cut-off time (s)

A = Area of field to be irrigated (m^2)

D = Irrigation depth (mm)

Q = Discharge rate (Ls^{-1})

Soil Hydraulic Conductivity: The soil hydraulic conductivity was determined by conducting infiltration experiments, at the harvest of each cropping season. The infiltration data were collected from three positions covering head, middle and tail section of each treatment, using double ring infiltrometer. Both the rings were inserted to more than 5 cm depth into the soil to avoid lateral preferential flow. The outer buffer ring and inside rings were filled simultaneously over a polythene sheet which was gradually released to the soil by sliding the polythene sheet and then immediately filling the water deficit to the designated level already marked on rings surface. The data collection was immediately started by recording the volume of water added and time elapsed by keeping the water level constant in the rings, until a constant value (steady state) of volume and time was reached. The rings were located on top of beds, at furrow and flat basins during both experimental periods.

Crop Yield and Water Productivity: The crop yield data were collected by using sample size of 1.8 m^2 (1.8 m and 1 m) during experiment 1 and 1.3 m^2 (1.3 m x 1 m) during experiment 2 for all treatments to ensure accommodating the whole bed width, while accounting for both cultivated bed area and uncultivated furrow area. Three samples were collected from the head, middle and tail sections of all treatments. The samples were sundried which generally took around two weeks for complete drying and total dry biomass and dry grain weights were determined for all samples, after carefully separating the straw and grains manually.

The water productivity W.P. (kg m^{-3}) was calculated according to equation 5. The total water input was comprised of cumulative irrigation application, total rainfall during the cropping season and any difference (+ve/-ve) of soil moisture at sowing and harvest. The rainfall data was collected at the experimental area using manual rain gauge.

$$W.P. = Crop\ Yield \times Water\ Input^{-1} \qquad (5)$$

All the data were analyzed using Microsoft excel 2007 spread sheet and inbuilt commands of average, standard deviation and graphical display of results. All the data sets were checked for compliance with the underlying ANOVA assumption, before applying the statistical analysis for determining the significant differences between the different treatments (groups). The data collection times during both cropping seasons are summarized in Table 1.

Table 1: *Crop and soil data collection times during the experimental period (2000-2009) under wheat-maize cropping pattern in Mardan district of Khyber Pakhtunkhwa*

Crop	Sowing Time	Time period/dates of data collection		
		Infiltration	Bulk Density	Crop yield / Harvest time
Maize	June 15 to 30	May 15 to 20	7 times per season	September 25 to 30
Wheat	November 10 to 25	October 15 to 20	5 times per season	April 25 to May 5

Results

Soil Bulk Density and Hydraulic Conductivity

The soil bulk density data showed a decreasing trend for raised beds compared with flat basin during both experimental periods as given in Figure 3. The bulk density of WB was significantly reduced at 5% level of significance during the first experimental period. Similarly, the bulk density of MB and NB was significantly reduced at 5% level of significance when compared with FB but the difference was not significant between NB and MB within the experiment 2.

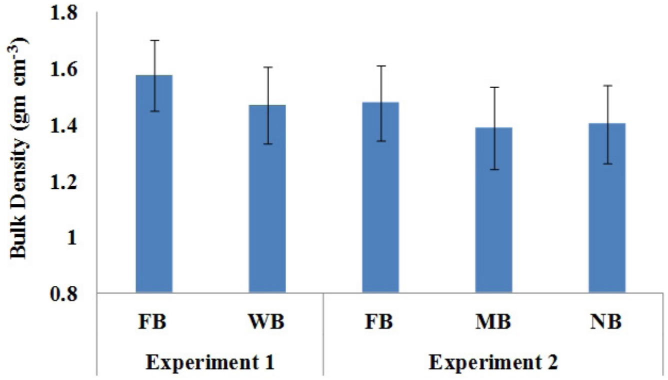

Figure 3: *Average bulk density variations among treatments (FB-Flat Basin, WB-Wide bed, MB-Medium Bed and NB-Narrow Bed) during two experimental periods (Experiment 1: 2000-2004, Experiment 2: 2005-2009) under wheat maize cropping pattern (vertical bars show SD)*

The hydraulic conductivity of different raised bed sizes demonstrated significantly increased values at 5% level of significance for WB during experiment 1 and for MB and NB during experiment 2 compared with FB respectively (Figure 4). Interestingly, the hydraulic conductivity of NB was significantly reduced than MB during experiment 2. The reason might be the greater soil compaction due to greater mechanical activity on NB compared with MB. The hydraulic conductivity of furrow was the least among all treatments and was significantly reduced than all other treatments.

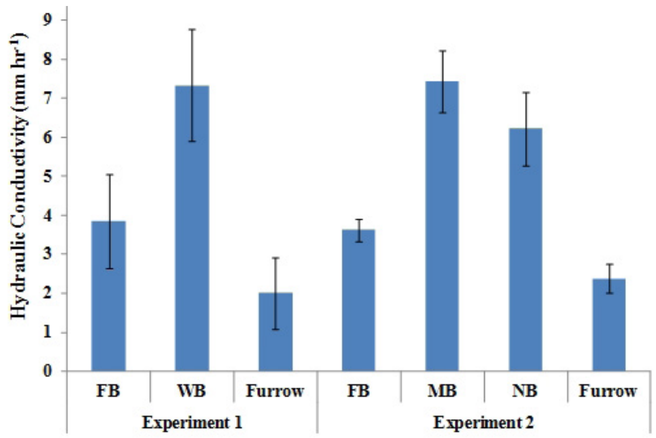

Figure 4: *Comparison of average soil hydraulic conductivity for different raised beds (WB: Wide Bed, MB: Medium Bed, NB: Narow Bed), furrows and flat basin (FB) during two experiments (Experiment 1: 2000-2004 and Experiment 2: 2005-2009) under wheat maize cropping pattern (vertical bars show SD)*

Total Water Input

For wheat crop, the irrigation application for WB and MB was significantly reduced at 5% level of significance compared with FB during experiment 1 and 2, respectively (Figure 5). Greater furrow spacing on WB compelled for reduced water application per unit area, thus the furrow were slightly overtopped and maintained at full level with reduced inflow rate for a while to confirm lateral water movement to bed middle and fulfil crop water requirement. However, visual observation showed greater dry bed middle area on WB compared with MB after irrigation was applied, which delayed wheat crop germination and negatively affected crop health in bed middle, especially when early season rainfall did not occurred during wheat season. However, the irrigation application during experiment 2 was not significantly different between NB and MB.

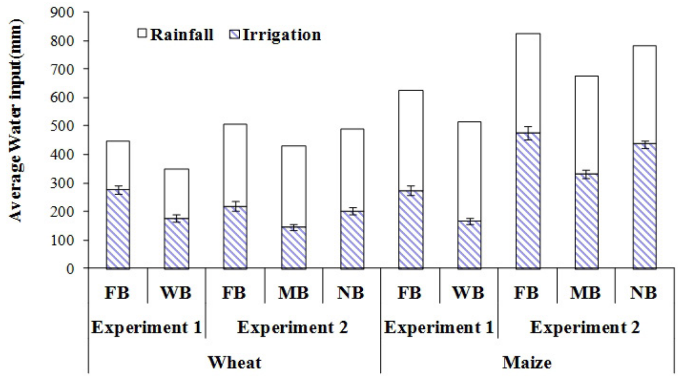

Figure 5: *Total water input for different raised bed sizes (WB, MB and NB) compared with flat basin (FB) during two experiments (Experiment 1: 2000-2004 and experiment 2: 2005-2009) under wheat maize cropping pattern (vertical bars show SD)*

For maize crop, irrigation applications were again significantly reduced for WB and MB treatments but not significant for NB at 5% level of significance when compared with FB during both experiments as shown in Figure 5.

Crop Yield

The wheat crop yield was significantly higher at 5% level of significance on WB and MB compared with FB and NB during both experiments under wheat crop season (Figure 6). However, the yield of WB and MB were comparable during both experiments. The expected increased crop yield on WB due to increased cropped area compared with MB was compromised by the reduced crop yield on bed middle area due to dry bed middle. For maize crop the crop yield was significantly higher for WB, MB and NB than FB during both experiments at 5% level of significance.

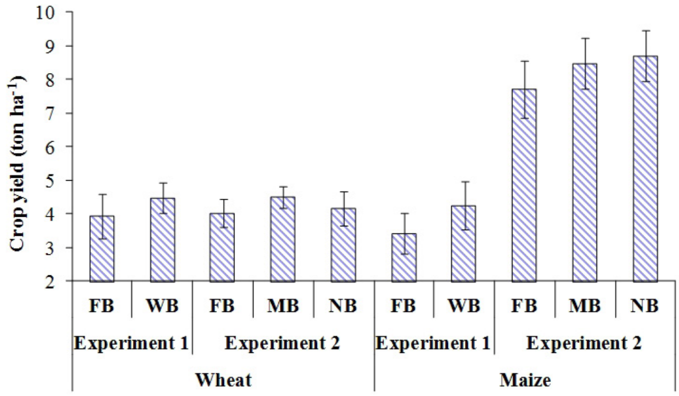

Figure 6: *Impact of different raised bed sizes (WB, MB, NB) compared with flat basin (FB) on crop yield during two experiments (Experiment 1: 2000-2004 and experiment 2: 2005-2009) under wheat maize cropping pattern (vertical bars show SD)*

However, the maize yield for MB and NB was comparable during experiment 2. Interestingly, the maize yield during experiment 1 was significantly less than experiment 2 due to change in crop variety from local during experiment 1to pioneer hybrid seed during experiment 2.

Water Productivity

The water productivity of wheat crop was significantly higher for WB and MB than FB at 5% level of significance during both experiments (Figure 7). However, the water productivity of NB and FB was comparable during experiment 2. For maize crop the water productivity of WB, MB and NB were significantly higher than FB during both experiments. Similarly, the water productivity of MB was significantly higher for MB than NB during experiment 2.

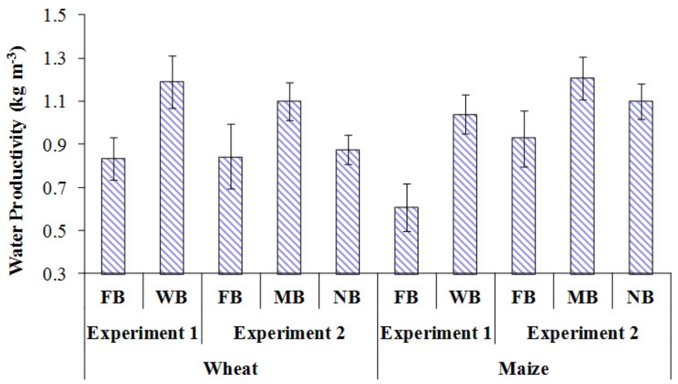

Figure 7: *Impact of different raised bed sizes (WB, MB, NB) and flat basin (FB) on water productivity during two experiments (Experiment 1: 2000-2004 and experiment 2: 2005-2009) under wheat maize cropping pattern (Vertical bars show SD)*

Discussion

Water productivity may be affected by two major factors related to agronomic and irrigation management (Akbar, 2013). Agronomic management should be aimed to improve soil physical, chemical and biological properties, crop health and land use efficiency. This can largely be accomplished by optimizing the soil management techniques, bed-furrow configurations and cropping management. Irrigation management should be aimed to minimize water losses and maximize irrigation application uniformity through optimizing inflow rate, time to cut-off, application depth and field design. This study showed that raised bed with reduced tillage under controlled traffic system enhanced soil physical properties and increased irrigation efficiency compared with traditional intensively tilled flat basin practice, which raised the prospects of increased irrigation performance on farms by replacing the traditional flat basin with this system.

A significantly reduced bulk density and increased soil hydraulic conductivity were identified when controlled traffic farming was emplaced for four consecutive years under raised beds with wheat-maize cropping pattern. These results conforms to the finding of Tullberg and Murray (1988), who identified six fold increase in soil infiltration while (McHugh et al., 2009) identified up to 45% increase in plant available water and 9% decrease in bulk density in the top 40 cm profile over a 3 year period of controlled traffic farming in comparison with random traffic under Queensland Vertisol. Other benefit of confining field traffic to furrows only tended to compact furrow bottom, which reduced vertical infiltration and increased lateral infiltration, thus helped in reducing crop water stress in the middle of 180 cm wide beds and has the potential to expedite irrigation water advance up to 45% according to Allen and Musick (1992), which helped in increasing the irrigation efficiency.

Intensive tillage destroy soil structure stability by temporarily increasing the soil macro porosity, which collapses during the subsequent early crop growing season (Coquet et al., 2005; Bormann and Klaassen, 2008), while porosity and soil infiltration gradually enhances under the reduced tillage system (Azooz and Arshad, 1996) as noted in the current study. Similarly, intensive tillage leaves the soil exposed to structural decline, destroys stable bio pores and fauna (Smith et al., 1983) and exacerbates soil carbon and organic matter loss. Hence, due to effects on soil physical, chemical and biological properties, tillage needs to be minimized for improving soil physical properties and increasing farm profitability due to reduced operational cost. The current study demonstrated reduced water input and increased crop yield for controlled traffic raised beds compared with traditional flat basin under intensive and randomly tilled system. All these factors led to increased water productivity for raised beds compared with flat basin.

Wider beds are preferred to narrow bed, because it increases land use efficiency, reduce irrigation application and save un-cropped furrow area (Jin et al., 2007). However, optimum bed width is influenced by lateral infiltration potential, which depends on soil type, soil structure, infiltration opportunity time, water level in furrow or inflow rate (Akbar et al., 2015). The wide beds with 180 cm furrow spacing was identified larger than optimum bed size for fulfilling crop water requirement uniformly across the bed width, thus suffered reduced crop yield in bed middle. The MB may also reduce crop yield in bed middle under current soil and irrigation condition if not properly managed.

Conclusions

The improved soil properties (reduced bulk density up to 7% and increased hydraulic conductivity up to 106%), reduced irrigation applications (up to 40%), increased crop yield (up to 25%) and increased water productivity (up to 71%) illustrates the prospects of enhanced food security and sustainable agriculture by replacing the traditional tillage intensive farming systems with CTRBF system for majority of crops and vegetables in the country.

Wider beds can saves irrigation water losses and can increases land use efficiency by accommodating more crop rows and reducing un-cropped furrow area, but requires controlled and optimized land and water management for minimizing yield loss due to reduced lateral infiltration into the bed middle under different soil types.

Recommendations

The controlled traffic raised bed farming system need to be evaluated under the wide environmental conditions and cropping patterns of Pakistan, especially in the Indus Basin.

The controlled traffic raised bed farming system requires mechanized farming, thus needs detailed economic analysis and identification of measures for its adoption under the existing socio economic conditions of farming communities.

Acknowledgment

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Authors' Contribution

Ghani Akbar contributed in establishing the experimental plots, played a key role in data collection, data analysis, writing this paper and paper correspondence and Muhammad Munir Ahmad supported in experimental design, data analysis and review. Muhammad Asif supported in data collection and establishment of experimental plots. Iqbal Hassan helped in data collection and experimental plots establishment. Qurban Hussain contributed in data analysis and reviewing the paper. Greg Hamilton contributed in financial management through Australian Centre for International Agriculture Research (ACIAR), supported in experimental design, data analysis, writing and review.

References

Ahmad, N., M. Arshad and M.A. Shahid. 2009. Bed-furrow system to replace conventional flood irrigation in Pakistan, 60th International Executive Council Meeting & 5th Asian Regional Conference, New Delhi, India.

Akbar, G. 2013. Identifying Strategies for Improving Water Productivity of Permanent Raised Beds, PhD thesis, University of Southern Queensland (USQ), Toowoomba, Australia.

Akbar, G., S. Raine, A. McHugh and G. Hamilton. 2015. Managing lateral infiltration on wide beds in clay and sandy clay loam using Hydrus 2D. Irrig. Sci. 33:177-190. http://dx.doi.org/10.1007/s00271-014-0458-9

Allen, R. and J. Musick. 1992. Furrow traffic and ripping for control of irrigation intake. Appl. Engineer. Agric. 8:243-248. http://dx.doi.org/10.13031/2013.26060

Azooz, R. and M. Arshad. 1996. Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. Canad. J. Soil Sci. 76:143-152. http://dx.doi.org/10.4141/cjss96-021

Bakker, D., G. Hamilton, R. Hetherington and C. Spann. 2010. Productivity of waterlogged and salt-affected land in a Mediterranean climate using bed-furrow systems. Field Crops Res. 117: 24-37. http://dx.doi.org/10.1016/j.fcr.2010.01.009

Bormann, H. and K. Klaassen. 2008. Seasonal and land use dependent variability of soil hydraulic and soil hydrological properties of two northern German soils. Geoderma. 145: 295-302. http://dx.doi.org/10.1016/j.geoderma.2008.03.017

Coquet, Y., P. Vachier and C. Labat. 2005. Vertical variation of near-saturated hydraulic conductivity in three soil profiles. Geoderma. 126: 181-191. http://dx.doi.org/10.1016/j.geoderma.2004.09.014

Dingman, S.L. 2002. Water in soils: Infiltration and redistribution. Physical Hydrology (Second edition). Prentice-Hall, Inc., Upper Saddle River, New Jersey. pp. 646. ISBN 0-13-099695-5.

Hamilton, G., D. Bakker, D. Houlbrooke and C. Span. 2005. Raised Bed Farming in Western Australia. Bulletin 4646, Department of Agriculture, Western Australia.

Hassan, I., Z. Hussain and G. Akbar. 2005. Effect of permanent raised beds on water productivity for irrigated maize-wheat cropping system. In: Evaluation and performance of permanent raised bed cropping systems in Asia, Australia and Mexico (eds. C. Roth, R. Fischer and C. Meisner). ACIAR Proceeding No 121, Griffith, NSW, Australia. pp. 59-65.

Hulugalle, N.R. and I.G. Daniells. 2005. Permanent beds in Australia cotton production systems. In: Evaluation and performance of permanent raised bed cropping systems in Asia, Australia and Mexico (eds. C. Roth, R. Fischer and C. Meisner). ACIAR Proceeding No 121, Griffith, NSW, Australia. pp. 162-172.

Jin, H., L. Hongwen, N. Kuhn, Z. Xuemin and L. Wenying. 2007. Soil loosening on permanent raised-beds in arid northwest China. Soil Tillage Res. 97: 172-183. http://dx.doi.org/10.1016/j.still.2007.09.016

Kahlown, M., M. Shafique and M. Iqbal. 1998. Improved irrigation methods for efficient use of irrigation water under different water-table depths. Mona Reclamation Experimental Project, WAPDA, Sargodha, Pakistan.

Kalwij, I.M. 1997. Assessing the field irrigation performance and alternative management options for basin surface irrigation systems through hydrodynamic modelling, Managing irrigation for environmentally sustainable agriculture in Pakistan, Surface irrigation methods and practices. IWMI, Lahore, Pakistan.

Li, Y., J. Tullberg and D. Freebairn. 2001. Traffic and residue cover effects on infiltration. Soil Res. 39: 239-247. http://dx.doi.org/10.1071/SR00017

Limon-Ortega, A., B. Govaerts, J. Deckers and K.D. Sayre. 2006. Soil aggregate and microbial biomass in a permanent bed wheat–maize planting system after 12 years. Field Crops Res. 97:302-309. http://dx.doi.org/10.1016/j.fcr.2005.11.001

McGarry, D. 2003. Tillage and soil compaction. Conservation agriculture: Environment, farmers experiences, innovations, socio-economy, policy. pp. 307-316.

McHugh, A., J. Tullberg and D. Freebairn. 2009. Controlled traffic farming restores soil structure. Soil and Tillage Res. 104:164-172. http://dx.doi.org/10.1016/j.still.2008.10.010

Qureshi, A., P. McCornick, M. Qadir and Z. Aslam. 2008. Managing salinity and waterlogging in the Indus Basin of Pakistan. Agric. Water Manag. 95:1-10. http://dx.doi.org/10.1016/j.agwat.2007.09.014

Sayre, K. and P. Hobbs. 2004. The raised-bed system of cultivation for irrigated production conditions Sustainable agriculture and the international rice-wheat system. Marcel Dekker, Inc., New York (USA). pp. 337-355.

Shafiq, M., I. Hassan and Z. Hussain. 2002. Influence of Irrigation methods on the productivity of summer maize under saline/sodic environment. Asian J. Plant Sci. 6:678-680.

Smith, G., D. Yule and K. Coughlan. 1983. Soil physical factors in crop production on Vertosols in Qld. Australia International Workshop on soils-research in the tropics. Townsville.

Tullberg, J. and S. Murray. 1988. Controlled traffic in sub-tropical grain production. 11th Conference, International Society of Soil and Tillage Research Organization, Germany. pp. 323–327.

Tullberg, J., D. Yule and D. McGarry. 2007. Controlled traffic farming-From research to adoption in Australia. Soil Tillage Res. 97:272-281. http://dx.doi.org/10.1016/j.still.2007.09.007 http://dx.doi.org/10.1016/j.still.2007.09.008

Wang, X., H. Wu, K. Dai, D. Zhang, Z. Feng, Q. Zhao, X. Wu, K. Jin, D. Cai and O. Oenema.

2012. Tillage and crop residue effects on rain fed wheat and maize production in northern China. Field Crops Res. 132:106-116. http://dx.doi.org/10.1016/j.fcr.2011.09.012

William, T.L. and R.V. Whitman. 1969. Description of an Assemblage of Particles. Soil Mechanics (1st ed.). John Wiley & Sons, Inc. pp. 553. ISBN 0-471-51192-7.

World Bank. 1997. Staff appraisal report. Pakistan National Drainage Project Rural Development Sector Management Unit, South Asia Region. World Bank, Washington DC.