Compendium of Deliverables of the Conservation Agriculture Course 2014

Nele Verhulst, Michael Mulvaney, Rachael Cox,
Jelle Van Loon and Virginia Nichols (Editors)

CIMMYT
International Maize and Wheat Improvement Center

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International Maize and Wheat Improvement Center

Headquartered in Mexico, the International Maize and Wheat Improvement Center (known by its Spanish acronym, CIMMYT) is a not-for-profit agriculture research and training organization. The center works to reduce poverty and hunger by sustainably increasing the productivity of maize and wheat in the developing world. CIMMYT maintains the world's largest maize and wheat seed bank and is best known for initiating the Green Revolution, which saved millions of lives across Asia and for which CIMMYT's Dr. Norman Borlaug was awarded the Nobel Peace Prize. CIMMYT is a member of the CGIAR Consortium and receives support from national governments, foundations, development banks and other public and private agencies.

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Foreword

This book is the result of the hard work of 5 CIMMYT trainees who work on sustainable practices in India, Ethiopia and Zimbabwe, and participated in the 2014 visiting scientist program "Conservation agriculture: Laying the groundwork for sustainable and productive cropping systems". Over 5 weeks the scientists received an intense training program that combined mentoring and problem solving approaches. They actively participated in the ongoing cropping systems management activities of CIMMYT's Global Conservation Agriculture Program, Latin-America, at the experimental stations near Mexico City at El Batán and Toluca, and in nearby farmers' fields. Emphasis was given to conservation agriculture-based technologies for both irrigated and rainfed conditions: reduced tillage, using alternative crop residue management strategies and crop rotation. Wheat and maize were the main crops under study.

Strong emphasis was placed on the importance of interdisciplinary approaches. Breeders provided a better understanding of the nature of crop management by genotype interactions and plant pathologists improved the understanding of disease interactions with new tillage and crop residue management practices. These are just some of the numerous contributions we received from several CIMMYT scientists. Upon completion of the program, the participants presented their plans to initiate activities in their home countries. This included carrying out further research on what was learnt and the extension of the new technologies to farmers. They developed the necessary skills for trial management and plant and soil monitoring as influenced by management practices.

The main objectives of the program were:

- To enhance the understanding of the application of CA-based technologies and machinery (with an emphasis on planters/planter modifications) for irrigated and rainfed wheat and maize production systems
- To strengthen the ability to synthesize and apply the available knowledge related to CA-based technologies (seeding methodologies, irrigation water management, crop nutrient management, weed control strategies and crop residue management).
- To increase knowledge of long-term trial planning and management
- To develop the skills necessary to monitor soil and plant parameters as they relate to evaluating crop management practices
- To foster improved confidence, increased motivation, and a heightened appreciation of the benefits of team work and interdisciplinary research
- To strengthen participants' ability to generate scientifically-sound hypotheses, determine data collection strategies, and interpret data and summarize them into scientifically sound conclusions and recommendations

To achieve the last objective, each participant chose a deliverable to work on during the course. Some scientists analyzed and summarized data they brought from their home country, others reviewed a specific theme of interest related to conservation agriculture. In this book, we present the deliverables of each participant.

We want to thank the participants of the course for the excellent work they delivered. Each of you really did an excellent job. Thanks for sharing your valuable knowledge with the group.

Congratulations,

Nele Verhulst
Strategic Research Coordinator
Global Conservation Agriculture Program,
Latin-America

This book is the result of a training course and has to be considered as a product of the course rather than a reference book. The views expressed in the chapters are those of the corresponding author and do not necessary reflect the views of CIMMYT.

Chapter 1. Potential of conservation agriculture based maize-common bean system for increasing yield, soil moisture, and rainfall-use efficiency in Ethiopia

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Abstract

Conservation agriculture (CA) based intensification and stabilization of rainfed maize-legume cropping systems offers considerable promise for boosting productivity, improving food and nutrition security, and helping reverse the decline in soil fertility in parts of Africa. One of the immediate benefits of CA in dryland agriculture is improved crop yield through increased rainfall-use efficiency and soil water content. This study reports four years (2010-2013) of data concerning the effect of two tillage practices, CA and conventional practices (CP), on four maize (Zea mays L.) and common bean (Phaseolus vulgaris L.) cropping systems (maize-common bean intercropping, maize-common bean rotation, sole maize, and sole common bean) at the Melkassa Research Center in the Central Rift Valley in Ethiopia. Maize and bean grown in rotation under CA showed grain yield advantages of 28 and 40%, respectively compared to CP. CA increased stover weight of maize by 25% as compared to CP. Bean straw weight of the maize-common bean rotation in CA was increased by 34% compared with sole cropped common bean. Rainfall-use efficiency of maize was significantly improved by CA compared with CP in seasons with low rainfall (2011 and 2013). Maize-common bean rotation showed significantly higher rainfall-use efficiency compared with other cropping systems. Common bean rainfall-use efficiency was not affected by the tillage and cropping system except in 2012. In general, CA showed higher moisture content than CP. Hence, CA has potential to increase the productivity of rain water and could reduce the risk of crop yield reductions due to drought, as was apparent at the Melkassa Research Center in 2011 and 2013 when a period of moisture stress at grain filling affected CA treatments less than CP treatments.

1. Introduction

Conservation agriculture (CA) is a set of cropping principles aimed at sustaining high crop yields with minimum negative consequences on the environment. In practice, CA includes the simultaneous application of minimal soil disturbance, permanent soil cover through a mulch of crop residues or living plants, and crop rotations (Food and Agriculture Organization, 2014).

Benefits of CA systems in various countries have been widely published (Bolliger et al., 2006; Derpsch, 2008; Hobbs, 2007; Reicosky and Saxton, 2007; Wall, 2007). Comparing conventionally ploughed and CA systems, CA has exhibited higher infiltration and higher available soil moisture especially during critical crop development stages, which ultimately resulted in higher grain yield and therefore higher rainfall-use efficiency (Roth et al., 1988; Thierfelder, 2003). Results from East Africa and Colombia show that between 10 and 22% of rain water may be lost from an uncovered, ploughed soil surface (Thierfelder, 2003; Rockstrom et al., 2001). Higher infiltration rates, which may be observed in CA fields, prevent losses of surface water and soil (Lal, 1977; Shaxson and Barber, 2003). As a consequence of higher infiltration rates and reduced evaporation, general improvements in soil water status and water-holding capacity in CA systems can be observed (Bescansa et al., 2006; Derpsch et al., 1986). Other findings showed that higher infiltration rates, higher soil moisture contents (Derpsch et al., 1986; Roth et al., 1988; Roth, 1992), and absence of surface crusting (Shaxson and Barber, 2003) resulted from zero-tillage combined with surface mulch. Retention of crop residue translates to lower losses of moisture to evaporation in untilled soils covered with mulch compared to tilled soils (Dardanelli et al., 1994; Lal, 1990).

Research has shown CA can markedly reduce many components of soil degradation, including soil organic matter decline and soil structural degradation (Derpsch et al., 1986). Moreover, CA eliminates power-intensive soil tillage and reduces the drudgery and labor required for crop production by more than 50% for small scale farmers (Food and Agriculture Organization, 2014). Additionally, CA enables early planting, as land preparation is simplified and can be carried out before the first effective rains (Haggblade and Tembo, 2003). This may result in more efficient use of rainfall, reduced risk of crop failure when received below-average rainfall and stabilized yields when rains are poorly distributed (Friedrich, 2008; Erenstein, 2003).

After teff (*Eragrostis tef* L.), maize and common bean are the most important crops in the Central Rift Valley of Ethiopia (CRVE). Maize is a staple food crop, and common bean is an important source of protein. In addition, though less efficient in fixing N than other legumes, common bean was reported to fix up to 125 kg N ha^{-1} (Wortmann, 2006) and it is the most widely adapted and most commonly used species in maize-legume cropping system in the CRVE.

Crop yields in the semi-arid CRVE are limited by soil water storage, which is affected by both erratic precipitation and soil degradation. Thus variable climatic features and degraded soil are among the major constraints limiting the productivity of current cropping systems (e.g. conventional maize-legume system) in the CRVE. Via the aforementioned benefits, CA practices could help address these challenges. However, while there is ample evidence from on-station and on-farm experiments on the impact of CA in most parts of the world, there is scant information available on the impact of CA on maize-common bean system yield stabilization, rainfall-use efficiency and soil water storage in the semiarid CRVE. Information from this study could assist policy makers in developing policy which supports the adoption of CA where it is most effective. The objectives of this study were to (i) determine the effect of CA on maize and common bean yield, rainfall-use efficiency and soil moisture content and (ii) identify CA-based maize-common bean cropping systems suitable for the semi-arid CRVE.

2. Material and methods

2.1. Site description

Trials were conducted from 2010-2013 at the Melkassa Agricultural Research Center in the CRE located at 8°24'N, 39°12'E, and 1500 m altitude. The soil was a calcareous clay loam of volcanic parent material classified as a Typic Haplustand with low wet aggregate stability, a tendency for crusting, more than 1-m rooting depth, and slopes ranging from 0.02 to 0.04 m m^{-1}. Prior to establishment of the permanent flatbed trials in 2010, the site was used for conventional crop production for more than 20 years.

2.2. Experimental design and materials used

The experiment consisted of eight treatments in a split plot design with four replications conducted during the rainy season. The tillage practices were assigned to the main plots and the four cropping systems to the sub-plots. Subplots were 10 m wide and 20 m long. The conventional farmers tillage practice (CP) was compared with conservational agriculture (CA) practice. The CP in this area consists of ploughing the Andosols three times at shallow depths (10–20 cm) using an animal traction-based local plough referred to as a *maresha*, with residues being burned, grazed or removed and the remaining stubble incorporated with the *maresha*. In CA, seeds were seeded in an open hill using a hoe in un-tilled land with 100% surface crop residue retention.

The cropping systems investigated were: common bean rotated with maize (BM-rot; bean phase present in 2010 and 2012, maize in 2011 and 2013); intercropping 50% plant density common bean into 100% plant density of maize (53,333 plants ha^{-1}) two weeks after maize planting (BM-int), continuous sole planting of maize (M), and continuous sole planting of common bean (B). We used the maize variety Melkassa-II and common bean variety Nasir as they are commonly grown by smallholder farmers for their moisture stress tolerance.

Maize was planted at 75 cm and 25 cm inter- and intra-row spacing, respectively, giving a total maize plant population density of 53,333 plants ha^{-1} for all cropping systems. Bean was planted at 40 cm and 10 cm inter- and intra-row spacing, respectively, except for intercropping when bean was intercropped at inter- and intra-row spacing of 75 cm (between maize rows) and 10 cm, respectively.

Fertilizer diammonium phosphate (DAP) and urea were band-applied 5 cm from plant for CP and spot applied for CA at a rate of 100 kg DAP ha^{-1} at planting, and 50 kg urea ha^{-1} as side-dress applied 4 weeks after maize planting. Weed control was achieved using a pre-emergence application of glyphosate (N-(phosphonomethyl) glycine, 41% active ingredient) at a rate of 3 L ha^{-1} followed by regular hand-weeding as necessary for CA plots. Weeds were controlled manually for the CP plots.

2.3. Data collection

2.3.1. Crop data

Both grain and residue yield was taken from the middle four rows of the plots. At harvest maize ears and bean pods were removed from the plots, air dried and weight reported at 12% moisture. The remaining crop residues (maize stover and bean straw) were either retained (CA treatments) or removed (CP treatment). Maize stover and bean straw from the middle four rows was oven dried at a temperature of 75 °C for at least 48 hours. This dry weight was reported as residue yield.

2.3.2. Soil moisture data

Soil moisture contents at depths of 0-15 cm, 15-30 cm, 30-45 cm, and 45-60 cm were measured gravimetrically before planting and after harvest for 2010-2012 and only before planting for the 2013 crop season. Additionally, one access tube was installed in all treatments before harvesting in 2013. Moisture content was measured to 1 m depth with a capacitance probe (PR-2 probes, Delta-T Devices Ltd., UK). This data was separated into 0–10, 10–20, 20–30, 30–40 40–60 and 60-100 cm depths.

2.3.3. Rainfall-use efficiency (RUE)

Rainfall-use efficiency (RUE) was determined for each season as the ratio of dry grain weight (kg) to amount of accumulated rainfall (mm) from planting to physiological maturity (Figure 1).

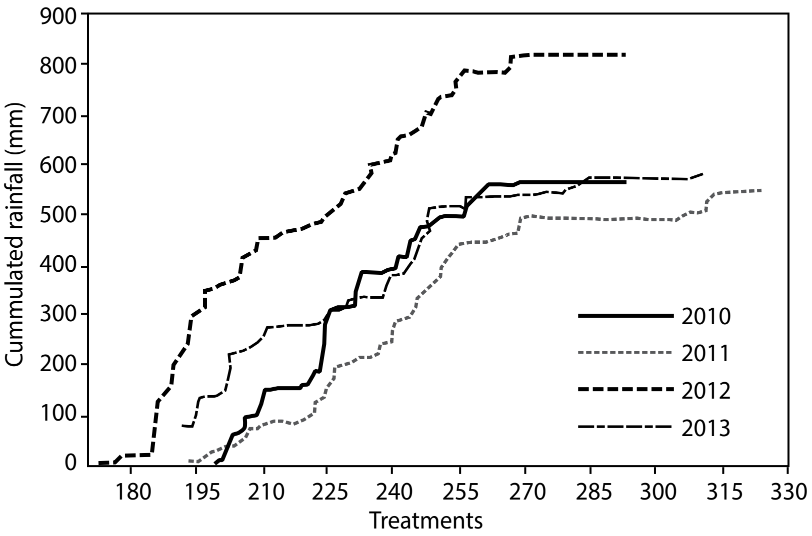

Figure 1. Rainfall distribution starting from planting date to physiological maturity during four crop seasons at Melkassa Agricultural Research Center; planting date varied depending on onset of rainfall.

2.4. Statistical analysis

Statistical analyses were carried out using STATISTIX-10 (Statistix, 2010) for grain yield, stover and straw weight, soil moisture, rainfall-use efficiency. Data were tested for normality. Analyses of variances (ANOVA) were conducted following the General Linear Model (GLM) procedure at 0.05 probability level. Where significance was detected, means were compared using least square differences (LSD). The photothermal quotient was determined as the ratio of daily solar radiation to accumulated degree days and rainfall data were analyzed using INSTAT climate guide software.

3. Results

3.1. Growing season characteristics

Onset of rainfall varied from season to season during the cropping years, with a maximum of 20 days difference between the earliest and latest onset (Figure 1). In 2012 we saw a relatively higher rainfall amount (818 mm) with more even distribution (smoother curve). In 2011 we saw the lowest amount of rainfall (554 mm), but 2010 and 2013 had the most variable distributions. In 2011 and 2013 we saw moisture stress during the grain filling stage. A high photothermal quotient was recorded in 2011 and 2013 (Figure 2).

3.2. Maize grain yield and stover weight

In 2013 the highest maize grain yields (5.76 t ha^{-1}) were recorded from the CA BM-rot, while the lowest maize grain yields (4.02 t ha^{-1}) were recorded from CP BM-int. The yield from BM-rot was significantly higher than yield from all CP treatments. Maize grain yield was higher with sole maize in CA than with other treatment years without maize on BM-rot (2010 and 2012), but the difference was not significant. In 2011, the BM-rot in CA produced ~40% more maize grain yield as compared to BM-rot in CP. In 2013, the main effects of cropping system, tillage, and production system significantly affected maize grain yield.

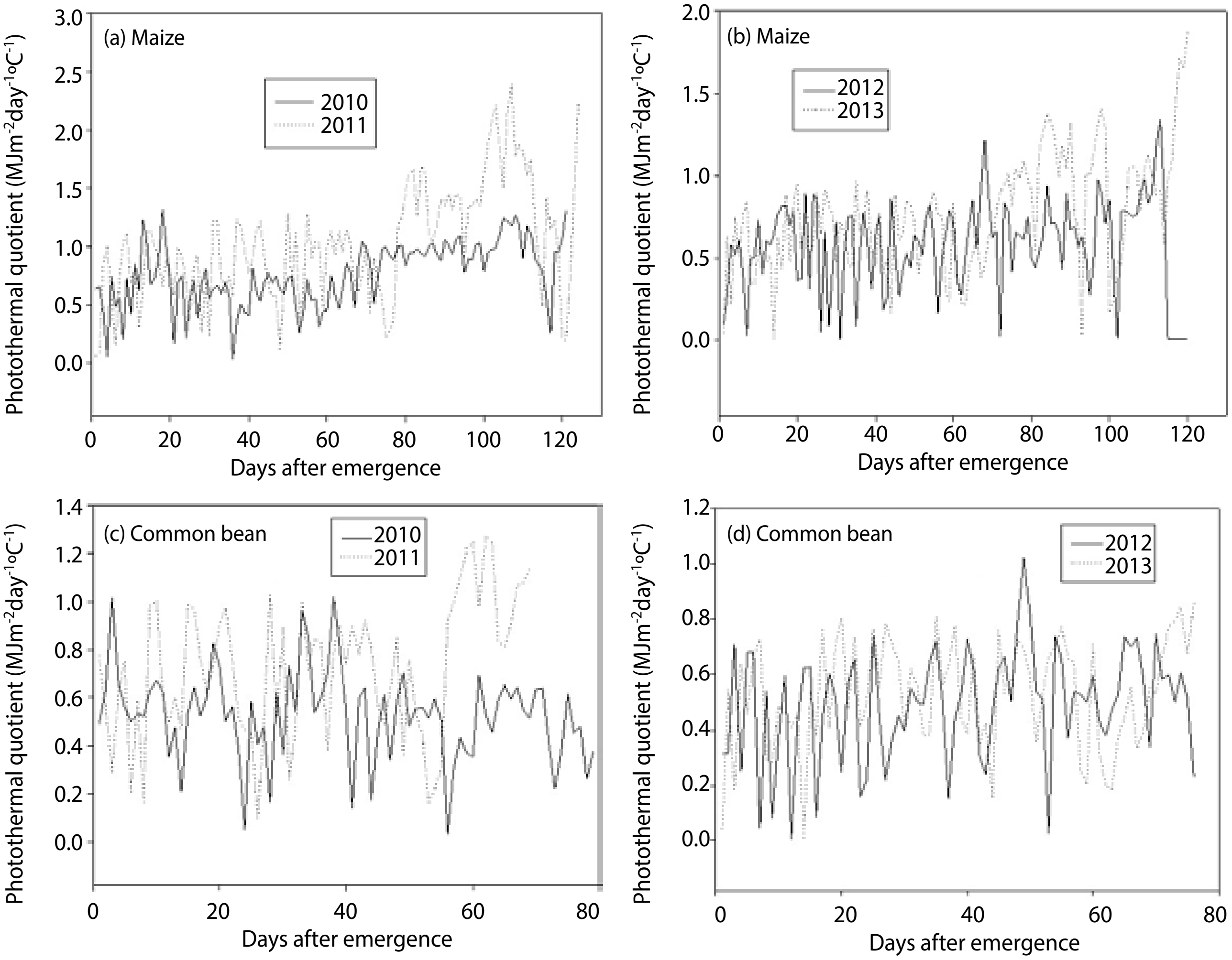

Figure 2. Photothermal quotient during maize (a and b) and common bean (c and d) growing seasons from emergence to physiological maturity at Melkassa Research Center in 2010-2013.

In general, maize stover production was higher in CA than in CP. Maize stover weight was not affected by main effects nor interactions of cropping system and tillage in 2010 nor 2012 (Table 1), while in 2011 and 2013 it was. The tillage by cropping system effect was due to greatest maize stover weight with CA and BM-rot cropping system in 2011 and 2013 as compared with the other cropping systems: the maize stover weight from CA BM-rot was 26% and 23% higher than CP intercropping in 2011 and 2013, respectively. In 2013 the highest stover weight came from BM-rot (12.65 t ha^{-1}) while the lowest came from BM-int (9.75 t ha^{-1}), leading to a significant effect of cropping system in 2013.

3.3. Common bean grain yield and straw weight

Grain yield of sole-cropped and rotated bean was not significantly affected by main effects of tillage, cropping system, nor production system in 2010-2012, results not presented for 2011 (Table 2). In 2012 BM-rot under CA also produced the highest grain yield (2.72 t ha^{-1}). Though the effect of tillage was not significant in 2010-2012, grain yield was generally greater with CA compared with CP (Table 2). Tillage significantly affected bean grain yield in 2013. The highest grain yield of 3.03 t ha^{-1} was recorded from CA, demonstrating a 28% yield increase as compared to CP.

Though bean straw weight was not significantly affected by tillage, cropping system, nor production system in 2011 (results not presented), 2012 and 2013, higher bean straw weight was consistently seen in CA BM-rot (Table 2). In 2010, straw weight was significantly affected by tillage, cropping system and production system (the combination of tillage and crop rotation). The highest straw weight of 6.98 t ha^{-1} was observed in CA BM-rot, which was 34% higher straw yield compared with CP sole bean.

Table 1. The effect of tillage, cropping system and production system on maize grain yield and stover weight at Melkassa Research Center in 2010-2013.

	2010		2011		2012		2013	
	Grain (t/ha)	Stover (t/ha)	Grain (t/ha)	Stover (t/ha)	Grain (t/ha)	Stover (t/ha)	Grain (t/ha)	Stover (t/ha)
Tillage								
CP[a]	4.2a*	8.1a	3.72a	8.63b	3.6a	10.0a	5.37a	10.81a
CA[b]	3.9a	9.9a	4.35a	9.76a	3.9a	13.3a	4.42b	10.75a
Cropping System								
Sole maize	4.6a	9.4a	4.19a	8.86b	3.7a	11.2a	4.74b	9.95b
BM[c] rotation	-	-	4.14a	10.01a	-	-	5.34a	12.65a
Intercropping	3.6a	8.65a	3.77a	8.71b	3.7a	12.0a	4.59b	9.75b
Production System								
CP sole maize	4.6a	8.2a	3.90a	8.80b	3.6a	10.2a	4.27cd	10.10ab
CA sole maize	4.6a	10.5a	4.48a	8.93b	3.7a	13.9a	5.22ab	9.80b
CP BM rotation	-	-	3.69a	8.83b	-	-	4.97bc	11.96ab
CA BM rotation	-	-	4.60a	11.2a	-	-	5.76a	13.33a
CP intercropping	3.9a	7.9a	3.57a	8.26b	3.6a	9.8a	4.02d	10.20ab
CA intercropping	3.2a	9.4a	3.96a	9.16b	3.9a	12.6a	5.16ab	9.30b

[a] Conventional practice; [b] Conservation agriculture; [c] Bean-maize

* Means within the same season (same column) followed by the same letter column for the main effects are not significantly different at the 0.05 probability level, LSD-test.

Table 2. The effect of tillage, cropping system and production system on common bean grain yield and straw weight at Melkassa Research Center.

	2010		2012		2013	
	Grain (t/ha)	Straw (t/ha)	Grain (t/ha)	Straw (t/ha)	Grain (t/ha)	Straw (t/ha)
Tillage						
CP[a]	2.17a*	5.16b	2.17a	5.25a	2.18b	4.08a
CA[b]	2.65a	6.34a	2.57a	5.68a	3.03a	4.70a
Cropping System						
Sole bean	2.49a	5.16b	2.27a	5.21a	NA	NA
BM[c] rotation	2.34a	6.34a	2.47a	5.72a	NA	NA
Production System						
CP sole bean	2.21a	4.63b	2.12a	5.10a	NA	NA
CA sole bean	2.78a	5.70ab	2.43a	5.30a	NA	NA
CP BM rotation	2.14a	5.70b	2.23a	5.40a	NA	NA
CA BM rotation	2.53a	6.98a	2.72a	6.10a	NA	NA

[a] Conventional practice; [b] Conservation agriculture; [c] Bean-maize

* Means within the same season (same column) followed by the same letter column for the main effects are not significantly different at the 0.05 probability level, LSD-test.

Straw weight of BM-int was not affected by tillage in 2010 and 2012 (Table 3). However, CA attained a 27% and 31% increase in straw weight compared to CP in 2010 and 2012, respectively. On the other hand, straw weight of BM-int was significantly affected by tillage in 2011 and 2013. CP had 12 % higher straw weight compared to CA in 2011, but CA had 57% higher straw weight compared to CP in 2013.

3.4. Rainfall-use efficiency (RUE) of maize and common bean

Maize RUE was only affected by production system in the 2013 cropping season (Table 4). The 2012 cropping season was characterized by high rainfall amounts (Figure 1) and low RUE. The 2011 cropping season was characterized by low rainfall and maize grown in CA had a RUE 12% higher than CP, although the difference was not significant. In 2013, the highest RUE was from CA BM-rot (10 kg grain mm^{-1}), and BM-rot showed significantly higher RUE compared to BM-int and sole bean. Common bean RUE was not significantly affected by tillage, cropping system nor production system. (Results not presented).

3.4. Soil moisture content

Moisture content of the soil horizons was significantly affected by treatments in all season soil horizon combinations except at harvest in 2013 for 15-30 cm and 30-60 cm (Figure 3). In 2011, the effect of treatments on soil moisture content was inconsistent at planting time but sole maize grown in CA showed higher moisture content across the soil horizons after harvest. There was higher moisture content at deeper depth (30-60 cm) both during planting and after harvest. In 2012, BM-rot in CA showed higher moisture content consistently in all soil horizons, and moisture was 34% higher within the first 15 cm soil depth as compared to CA sole maize at planting. The lowest moisture content at harvest in 2012 was in the CP BM-int. In 2013, we saw higher soil moisture content in all soil horizons in the CA BM-rot plots followed by CA sole maize at both planting and after harvest.

4. Discussion

Rainfall was variable in onset, poor in distribution, and stayed for a shorter time (on average 95 days) with rain ceasing at maize grain filling stage during the four study years. These rainfall conditions would tend to affect grain yields of maize as opposed to maize stover weight. The greater photothermal quotient in 2011 and 2013 was due to high solar radiation and lower growth degree days, and this might have affected dry matter accumulation and partitioning. A high source strength due, for example, to high irradiance strongly enhances the total plant growth, but information on the effect of source strength on the partitioning of assimilates among the plant organs is limited (Marcelis, 1996).

Table 4. The effect of tillage, cropping system and production sytem on RUE of maize in 2010-2013 crop seasons.

	Rainfall-use efficiency (kg mm^{-1})			
	2010	2011	2012	2013
Tillage				
CP[a]	7.5a^{r}	6.8a	4.4a	7.6a
CA[b]	7.0a	8.0a	4.7a	9.3a
Cropping System				
Sole maize	8.2a	7.7a	4.6a	8.2b
BM[c] rotation	-	7.6a	-	9.2a
Intercropping	6.3a	6.9a	4.6a	7.9b
Production System				
CP sole maize	8.1a	7.2a	4.4a	7.4cd
CA sole maize	8.2a	8.2a	4.7a	9.0ab
CP BM rotation	-	6.8a	-	8.6bc
CA BM rotation	-	8.4a	-	10.0a
CP Intercropping	6.9a	6.6a	4.7a	7.0d
CA Intercropping	5.7a	7.3a	4.7a	8.9ab

[a] Conventional practice; [b] Conservation agriculture

* Means within the same season (same column) followed by the same letter are not significantly different at the 0.05 probability level, LSD-test.

Table 3. The effect of tillage on intercropped common bean grain yield and straw weight Melkassa Research Center.

	2010		2011		2012		2013	
	Grain (t/ha)	Straw (t/ha)	Grain (t/ha)	Straw (t/ha)	Grain (t/ha)	Straw (t/ha)	Grain (t/ha)	Straw (t/ha)
CP[a]	0.68a*	0.53a	0.51b	0.66a	0.57a	0.91a	0.34b	0.30b
CA[b]	0.78a	0.73a	0.84a	0.58b	0.66a	1.31a	0.76a	0.72a

[a] Conventional practice; [b] Conservation agriculture

* Means within the same season followed by the same letter in column are not significantly different at the 0.05 probability level, LSD-test.

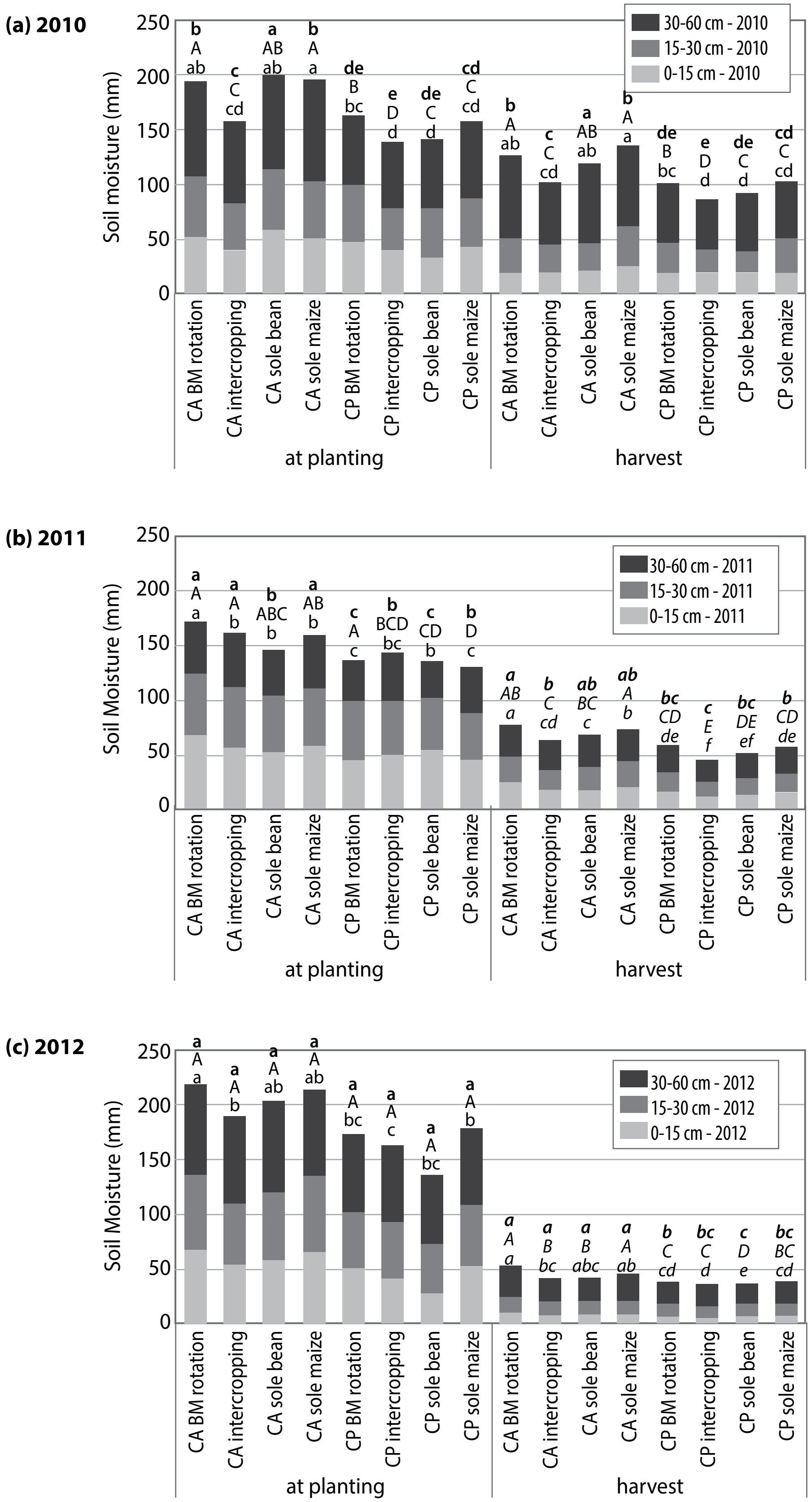

Figure 3. Production system effects on soil moisture content at planting and harvesting in (a) 2010 (b) 2011 (c) 2012.

BM: Bean maize; CP: Conventional practice; CA: Conservation agriculture. Letters indicate significant differences between cropping systems within a season at a 0.05 probability level. Bold lowercases letters represent differences at the 30-60 cm depth, uppercase at the 15-30 cm depth, lowercase at the 0-15 cm depth.

Although there is some evidence that CA does not show yield gains during the first year of establishment, both the BM-rot and sole maize under CA had better grain yield than sole maize under CP during the first year (2010). This might be due to application of appropriate crop and soil management practices suitable to the study site during the experimental period. In 2011, the 40% yield advantage from BM-rot under CA as compared to CP might be due to crop residue mulch, which would likely reduce water evaporation from the soil (Dardanelli et al., 1994; Lal, 1990), in addition to the benefits from rotating with a nitrogen fixing legume. Similar results have been reported in a no-till study done in South Africa, showing substantial maize yield increases in maize following legumes compared to continuous maize (Thierfelder et al, 2012). In 2011 and 2013, the low maize grain yield and stover weight of BM-int under CP might be due to competition for moisture between maize and common bean combined with high water evaporation from bare CP plots during the high radiation. Thus, intercropping in CP could significantly decrease the yield of the main crop in a season with lower amounts and/or poorly distributed rainfall.

The absence of significant differences among the treatments for the bean grain yield in the first three years of study could be due to the sufficiently long growing period for common bean. Again, the water-stressed 2011 and 2013 seasons (Figure 1) may have exposed differences between CA and CP, due to the mulching effect of residue. The highest yield advantage of CA (more than 35%) for BM-int in 2011 and 2013 could be due to more water available to crops from conserved moisture in the soil during the stress years and hence less competition between intercropped plants. Plots under CA produced the highest stover weights of maize and straw weight of bean in all seasons, mainly in BM-rot. This indicates BM-rot under CA may be highly suitable for Central Rift Valley of Ethiopia.

Relatively low RUE in the 2012 cropping season could be due to the high rainfall received during the cropping period. The highest RUE of CA occurred during seasons with low rainfall, indicating CA can produce a better yield with low water resources in the semi-arid regions of Ethiopia. Moreover, higher RUE of maize and common bean in a rotation system confirms suitability of the CA-based BM-rot system for the region. One of the immediate benefits of CA in dryland agriculture is improved RUE, likely through increased water infiltration and decreased evaporation from the soil surface, with in turn is associated with decreased runoff and soil erosion. In general, CA showed higher soil moisture content in both good and bad seasons of the CRVE. In our study, higher soil moisture in CP and CA in the deepest layer are likely to be a result of the inability of maize and common bean plants to grow up to a depth of 60 cm and make use of this water. Working on soils in Zimbabwe, Vogel (1995) and Thierfelder and Wall (2009) found that although some maize root penetration was observed to about 75 cm, most of the soil water was accessed within the first 30 cm.

5. Conclusions

Under water-stressed years, a maize-common bean rotation under CA was especially productive for the semi-arid Central Rift Valley of Ethiopia. We attribute this to crop residue cover control on soil evaporation, and thus enhanced soil moisture. Yield of maize intercropped with common bean was more affected in seasons with less rainfall, likely due to competition for moisture. Systems under CA showed better RUE in all seasons, but the difference was larger in seasons with low rainfall, indicating CA may provide resilience in the Central Rift Valley of Ethiopia, where precipitation is often erratic. More in-depth studies on the impact of CA on soil infiltration rate, moisture content, soil carbon stock, runoff, soil nitrogen, soil phosphorus, and soil pH are needed to fully understand CA's potential in Ethiopia.

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Chapter 2. How to promote and implement conservation agriculture adoption in Ethiopian agriculture

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Executive Summary

Major challenges in Ethiopian agriculture include population growth and land degradation. Land degradation appears in the form of soil erosion, resulting in loss of soil fertility. Increasing population pressures and overgrazing have exacerbated soil erosion. Recent land rehabilitation measures have been implemented in Ethiopia to avert these situations, including community watershed management, sustainable land management and soil and water conservation structures on farmlands. Conservation agriculture (CA) has the potential to stop soil erosion at its source, and should therefore be included in revitalization efforts.

According to the Food and Agriculture Organization (FAO), CA is an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. Specifically, CA is characterized by three linked principles, namely:
1. *Continuous minimum mechanical soil disturbance*
2. *Permanent organic soil cover*
3. *Diversification of crop species grown in sequences and/or associations*

Research has shown CA reduces surface run off, improves soil quality, increases crop yields and increases resilience to climate change/drought – all of which lead to increased sustainability. Sustainability development programs which are already in place can be used as entry points for CA. Previously in Ethiopia CA was implemented by Sasakawa Global 2000 (SG2000) in parts of the Oromia and Amhara regions. The program resulted in the adoption of CA by many farmers, but after the SG200 phase out many farmers stopped practicing CA principles. The gradual decline of CA in the area could be a result of lack of extension support and packages relevant to the respective area's specific context. Policy formulation, design of extension approaches and package development for different agro-ecologies and crop systems are therefore a prerequisite for successful CA adoption and retention. Several options exist for supporting the adoption of CA, including conducting baseline studies, properly documenting good practices, sharing experiences and lessons learned from other countries and collaboration with experts in the field. These activities should all be carried out with the ultimate goal of implementing CA in Ethiopia.

At a more basic level, Ethiopia will require a shift in paradigms to implement CA on a large scale. Ethiopian universities and colleges should embrace CA principles in their curriculums, and teach the potential environmental and economic benefits. For this matter the Ministry of Agriculture (MoA) and Ministry of Education (MoE) should be work together in the development of CA curriculums and bench marks.

1. Introduction

Ethiopia struggles with myriad socio-economic and environmental challenges in its path to achieving sustainable development. The principal environmental problem in Ethiopia is land degradation in the form of soil erosion and loss of soil fertility. Land degradation is attributed to deforestation by farmers and loggers and urbanization. As a result, soil erosion and land degradation are typical phenomena in many areas. Unsustainable repeated and regular tillage practices are practiced on ecologically fragile farmland hillsides. The expansion of agriculture, due to increasing population and overgrazing, has accelerated soil erosion, especially on steeper slopes.

Cognizant of the widespread socio-economic and environmental consequences of land degradation, several land rehabilitation measures have been implemented in Ethiopia to avert the problem and restore degraded farmlands. Among the measures taken are community watershed management, sustainable land management programs, productive safety net programs and soil and water conservation structures. To date, conservation agriculture (CA) has not been included in these programs.

According to the FAO of United Nations (FAO 2003): *"Conservation agriculture is an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. Conservation agriculture is characterized by three linked principles, namely:*

1. *Continuous minimum mechanical soil disturbance*
2. *Permanent organic soil cover*
3. *Diversification of crop species grown in sequences and/ or associations*

Research has shown practicing CA principles contributes to land restoration and preservation by reducing surface run off, improving soil quality and productivity through soil organic matter accumulation, improving water infiltration, improving fertilizer efficiency, and increasing resilience to climate change/drought. Therefore, CA has the potential to contribute to many of Ethiopia's sustainable development approaches including Climate Resilient Green Economy (CRGE), watershed management, and sustainable land management. These sustainability development programs can be used as entry points for CA.

Almost two decades ago, CA was initiated by Sasakawa Global 2000 (SG2000) in parts of the Oromia and Amhara regions. Many farmers practiced CA principles, but after the SG200 phase out farmers started adjusting the CA principals to meet changing demands, which over time has meant abandoning many of the practices. The root causes for the gradual decline of CA in the area are lack of extension support and packages relevant to the respective area's context.

Additionally, local agronomists and extension agents are not formally trained in CA principles because Ethiopian universities have not incorporated these ideas into their curriculums.

2. Existing problems in Ethiopian agriculture

2.1. Rapid population growth

Rapid population growth leads to an increased demand for arable land. As deforestation occurs, energy sources for small holder farmers are shifting to include crop residues, cow dung and the remaining vegetation covers, which create a competing demand for crop residues. Growing public concern is focused on the immediate and short-term demands to growing populations. Land degradation and soil loss increase as population increases and pressures for social and economic development continue to drive more intensive agricultural activity. This problem is exacerbated by short-term economic gain, which frequently results in the acceptance of unsustainable activities such as regular and repeated cultivation and clearing of more lands in fragile ecological zones.

The population growth rate is highest in rural Ethiopia. The total population has more than doubled during the past three decades, from 29 million in 1972 to 67 million in 2002, and is expected to increase to 130 million by 2030 (CSA, 2012). In particular the highlands of Ethiopia are an area of high human and livestock densities, as well as the greatest degree of land degradation (Berry, 2003), as the majority of this population make their livelihood on land that is currently classified as severely degraded (FAO, 2003). Unless sustainable intensification of agriculture approaches such as CA are incorporated into existing development strategies, the agricultural productivity will decline.

2.2. Soil erosion

In Ethiopian agriculture, soil erosion presents economic and environmental challenges. Soil erosion causes depletion of soil organic matter, destroys soil structure, and reduces infiltration, all of which reduces yields (FAO, 1999). Recently hillsides and steep areas are being converted to farmlands at an alarming rate because of population growth and other land pressures. Crop resides are being used for animal feed, a source of household energy, and construction material. Farming communities focus on clearing new areas in forests and planting areas previously dedicated to pasture. Conversion to row crop agriculture promotes soil erosion because of intensive tillage practices and lack of soil cover for much of the year. Principles of CA address both of these concerns by promoting minimal soil disturbance and maintaining soil cover throughout the year. Ethiopia is among the most severely erosion-affected countries in the world (estimated at 10-13 mm per annum on average). Soil loss due to erosion varies, but losses range from 16 to 300 tons ha^{-1} year^{-1} depending on slope, land cover, soil types and rainfall intensities (Hawando, 1989). Acceleration of residue decomposition because of tillage also facilities soil erosion (FAO, 1999).

2.3. Drought and moisture stress

Ethiopia has a long history of drought, which greatly contributes to loss of life and resources. Recurrent drought combined with loss of soil and water narrow livelihoods of small holder farmers by exposing them to food shortage in the lean seasons. When drought is followed by strong rain, soil erosion and land degradation are aggravated and crop productivity is reduced significantly (FAO, 1999). Rainfed agriculture in Ethiopia is sensitive to late onset of rains, as well as early cessation, and patterns can be erratic and unpredictable in many parts of the country. The availability of water in the soil reduces the performance of crops and fertilizer efficiency (Rockstrom et al., 2010), therefore practices which buffer soil water content will benefit crop production.

Practices like CA which build or maintain soil organic matter and keep the soil covered to reduce losses to evapotranspiration will help manage soil water. Additionally, CA facilitates a better infiltration of rainwater, enabling the recharge of groundwater resources (Friedrich and Kassam, 2011).

2.4. Floods

During the rainy season in Ethiopia floods can result in loss of lives as well as development structures (FAO, 1999). Floods reduce crop yield by eroding topsoil, where organic matter and nutrients are available for crop growth. It also causes waterlogging in downstream farmland. Increased infiltration from CA on a landscape scale can lessen runoff, and residue can reduce the velocity of the runoff – both of which can help mitigate flood risks.

2.5. Gender issues and empowering women

Normally smallholder women farmers cultivate land by rented oxen. Because of the extensive land preparation normally practiced, many women plant late as male farmers only return to support women after they have planted their own fields. Reducing the time needed for land preparation via CA can allow women to plant in a more timely fashion, and decrease dependence on third parties for farming operations.

2.6. Competition for residues for various uses

In Ethiopia crop residues are used for both agricultural and non-agricultural activities. Potential uses include firewood, construction, roofing/thatching, animal fed and cash income. Of the total energy consumption 77% is from fire wood and charcoal, while 16% consists of crop residues. Additionally, crop residues provide highly valued fodder for livestock in the dry season when many East Africans face a shortage of animal feed (Giller et al., 2009).

Leaving residues in the field has been shown to have less tangible, but real benefits including increased water-use efficiency, reduced soil bulk density, increased cation exchange capacity, higher plant nutrient supply, and weed control. Programs which provide monetary incentives for leaving residues may be needed, as competition for residues is high in Ethiopia.

3. Benefits of CA

3.1. Economic benefits

Systems using CA principles have been shown to provide economic benefits resulting from various sources. Higher yields lead to higher gross incomes. Lower production costs due to decreased labor requirements for tillage also lead to increases in net income (Ngwira, 2012, Friedrich and Kassam, 2011).

On a landscape scale, CA could offer additional economic benefits. Severe organic matter depletion, driven by competing uses for crop residues and manure as livestock feed and fuel is estimated to reduce Ethiopia's agricultural GDP by 7%, while soil erosion costs Ethiopia US$1 to 2 billion each year (CRGE, 2011). Large-scale adoption of CA could therefore address these country-wide losses, in addition to providing farmers with a higher net income.

3.2. Environmental benefits

Practices associated with CA have been shown to offer a suite of environmental benefits. The CA principles of minimum soil movement, crop rotations/associations, and crop residue retention could significantly reduce greenhouse gas emissions (Flowler and Rockstorm, 2001). The principles of CA could also enhance carbon sequestration via building soil organic matter in the soil (Agegnehu et al., 2012). Crop residue retention may reduce water pollution by reducing both soil erosion and runoff (Erenstein, 2002). The presence of crop residues and soil cover increases the soil biota and the soil microbes, hastening breakdown of the remaining components of herbicides (e.g. paraquat and glyphosate).

3.3. Agronomic benefits

Through its alteration of water dynamics, crop reside retention improves nutrient availability and fertilizer use efficiency (Erenstein, 2002). The retention of the crop residues as mulch reduces losses of nutrient through leaching. Minimizing tillage can decrease the decomposition of organic matter, thus leading to accumulations. Crop rotation as an agronomic practice plays a significant role in pests and diseases control, and can therefore reduce the incidence of insect infestation and pathogen accumulation.

4. Challenges of CA adoption in Ethiopia

4.1. Lack of extension approaches and packages

Except in testing and experimental sites, farmers are undertaking one or two CA principles in separate fashions without linking principles (Tsegaye et al., 2008). Extension approaches for CA should vary with soil types, agroecologies, crops and indigenous practices of local farmers; CA needs to be flexible and create extension services suitable to different areas (FAO, 2006). Erenstein (2002) stated that a blueprint package is not likely to be successful and cannot fit in widely varying production systems in areas where different soil types, crops and diverse agroecologies exist.

Systems of CA are a combination of multiple technological disciplines, which involves experts from different fields such as agronomy, natural resource management, livestock, agroforestry, and energy. Certification of selected tools for CA is important for package development. The government should play pivotal roles in the adoption of CA by coordinating experts and supporting research, extension systems, testing and evaluation appropriate tools and machinery, and agronomic practices (Hengxin and Xuemin, 2006).

4.2. The mindsets of agriculture experts and farmers

For farmers who use repeated tillage, CA involves a relatively new concept of farming (Tsegaye et al., 2008). The concept of CA requires reforming of traditional farming systems through advocacy, awareness raising, capacity building and promotion as CA contradicts much of conventional farming knowledge and agronomic practices. The knowledge-intensive nature of CA systems and the need to tailor CA practices to local conditions demands strong problem-solving from researchers and extension staff. Farmers face challenges when they switch from repeated tillage practices to minimum tillage, including new weed management, new planting conditions, etc. According to some, costs of herbicides and labor in the area are determining factors for the uptake of CA (Erenstein, 2002).

5. Opportunities and Strategies of CA in Ethiopia

5.1. The existing traditional conservation farming practices

In many parts of Ethiopia small holder farmers are traditionally practicing a form of conservation based agriculture. Many small holder farmers practice minimum tillage, crop residue management in their farmlands and have community level bylaws to prevent the free access of animals into crop fields in the off seasons. These local bylaws can be entry points for CA in those regions.

5.2. The past experiences of CA by development partners

In Ethiopia, CA was introduced by development partners, non-government organizations (NGOs) such as Sasakawa 2000 and researchers. In such areas refreshment training is required to re-apply the three linked principles. Agriculture offices should provide extension support for small holder farmers so that CA can be scaled out by providing extension support for these small holder farmers.

5.3. Research results of CA

Research has been undertaken by the Ethiopian Institution of Agriculture Research (EIAR), agricultural universities and development partners. A collection of research results and implementation in the study areas can be entry points for adoption of CA in farmers' plots in the form of demonstration and pre-scaling.

5.4. Lesson from other countries

In promotion of CA, the government can apply publicizing CA related information, train development agents and farmers. Many countries are practicing CA for various reasons. Countries like China practice CA in order to rehabilitate degraded farmland because of population growth and overexploitation. In Australia CA is practiced to conserve moisture in the arid areas. CA in Brazil is undertaken to control soil erosions because of heavy rainfall. Many African countries are practicing CA to build climate resilient small holder farming systems.

Since 2002 the Chinese government has had special funds for conservation tillage extension projects. The Chinese Ministry of Agriculture (MOA) has been devoted to promoting the application of conservation tillage in China by means in accordance with Chinese situations (Hengxin and Xuemin, 2006). The experiences of different countries can be used as lessons for the adoption of CA under various situations of Ethiopian agriculture.

6. Conclusions and recommendations

We have seen that CA can contribute to restoration of degraded areas and preservation the existing fertile farmlands and can therefore be a component of watershed management, sustainable land management and Climate Resilient Green Economy of Ethiopia. Systems incorporating CA has wider benefits in particular for small holders and the nation in general. Economic and environmental benefits of CA could offer large scale benefits. CA needs due attention from policy makers to give weight and publicize the discipline to concerned bodies by creating suitable policies and extension systems to promote, adopt, expand among small holder farmers.

Through CA, vastly degraded areas in the highlands of Ethiopia could be restored and changed to productive lands. However, for the sustainability of CA practices the government should take the lead to formulate suitable policy, extension approaches and packages for different agro-ecologies and cropping systems. It must be noted that CA needs careful design for each particular situation; there are no blanket recommendations and blue prints for CA. As observed, many countries have started to incorporate CA in their agricultural sectors, and Ethiopia could easily follow suit. Unless the government provides support through policies and extension services CA will not be implemented on a wide scale.

Promoting the training of CA professionals, as well as the design of extension approaches and package development for different agro-ecologies and crop systems are a must. In order to hasten the process previous CA programs should be assessed by conducting baseline studies and collaboration with experts in the field and in other countries should be encouraged to facilitate easy adoption of CA in Ethiopia.

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Chapter 3. Effect of crop establishment methods on crop yield, weed dynamics, profitability and nutrient uptake in a rice-wheat cropping system of the Indo-Gangetic plains of eastern India

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Abstract

The rice–wheat cropping system covering 13.5 million ha in the Indo-Gangetic Plains in South-Asia is vital for food security. Water, energy and labor scarcity, increasing cost of production, diminishing farm profit, and the changing climate are major challenges faced by the farmers under intensive tillage-based conventional practices. In a field study, we evaluated productivity, weed dynamics, nutrient uptake and economical profitability of four wheat establishment methods during two years (four growing seasons). The wheat establishment methods included zero-till wheat (ZTW), Happy Seeder planted wheat (HSW), bed planted wheat (BPW) and conventional till wheat (CTW). The rice crop was puddle transplanted in all the plots. The treatments were completely randomized and replicated five times. Wheat grain yield under HSW was 3.4% and 4.1% higher than BPW, 8.3% and 11.0% higher than ZTW and 20.8% and 24.5% higher than CTW in 2012-13 and 2013-14, respectively. Content of N, P and K in wheat grain was also higher in HSW than in the other treatments. Weed density and biomass was the lowest under HSW followed by BPW, and the highest in CTW. The weed pressure was reduced in the second wheat growing season compared to the first. Rice yield was the highest under HSW and the lowest under CTW. Similar results were obtained for net profit and benefit cost ratio.

1. Introduction

Rice–wheat cropping systems are critically important for global food security, providing the staple grain supply for about 8% of the world's population (Timsina and Connor, 2001; Ladha et al., 2003). In South Asia, rice–wheat systems cover 13.5 million hectares with a marked concentration in India and the Indo-Gangetic Plains (IGP; Timsina and Connor, 2001). In the IGP wheat is grown in the cool and dry weather from November to March and rice is grown during the warm humid/semi-humid season from June to October. Rice–wheat systems encompass 23% of India's rice area and 40% of its wheat area, and rice and wheat together comprise 85% of India's cereal production (Timsina and Connor, 2001).

The Green Revolution boosted the productivity of rice–wheat systems through the introduction of high-yielding varieties and complementary technologies like irrigation and fertilizer in a supportive policy environment. However, recent studies indicate that the productivity is plateauing because of a fatiguing natural resources base; therefore sustainability of this cropping system is at risk (Kumar et al., 2002; Byerlee et al., 2003). Soil quality is governed primarily by the tillage practices used to fulfill the contrasting soil physical and hydrological requirements of the rice and wheat crop (Mohanty et al., 2007). Current crop cultivation practices in rice-wheat systems degrade the soil and water resources thereby threatening the sustainability of the system (Duxbury et al., 2000; Gupta et al., 2003; Ladha et al., 2003). The prevailing policy environment has encouraged inappropriate land and input use (Pingali and Shah, 1999) and crop system constraints have encouraged unsuitable responses. Developing and disseminating agricultural technologies that can save resources, reduce production costs and improve production while sustaining environmental quality is therefore becoming increasingly important (Gupta et al., 2002; Hobbs and Gupta, 2003). Farmers in the IGP in eastern India usually grow wheat after intensive dry tillage, planking, and using seed-cum-fertilizer drills. The tillage operations are energy and input intensive, and also create problems in timeliness of seeding of the succeeding crop (Bhushan et al., 2008; Jat et al., 2009). The tillage and crop establishment accounts for 25–30% of total wheat production costs in rice–wheat cropping systems of South Asia (Saharawat et al., 2011; Pathak et al., 2011), leading to lower benefit to cost ratios.

The conservation agriculture (CA) based resource conservation technologies (RCTs), practiced over 125 million hectare (m ha) area worldwide have proven to be energy and input efficient, improve production and income, and address the emerging environment and soil health problems (FAO, 2012, Saharawat et al., 2010, 2011; Gathala et al., 2011). The RCTs involve zero or minimum tillage with direct seeding using a seed-cum-fertilizer drill, bed planting, and Happy Seeder innovations in residue management to avoid straw burning, and crop diversification (Sharma et al., 2002; Gupta and Sayre, 2007). Farm mechanization plays a vital role for the success of CA-based RCTs in different agro-ecologies and socioeconomic farming groups. It ensures timeliness, precision, and quality of field operations; reduces production costs; saves labor; reduces weather risk in the changing climatic scenarios; improves productivity, environmental quality, sustainability, and generates rural employment both on- and off-farm (Ladha et al., 2009; Saharawat et al., 2011).

Soil cover with crop residues is an essential part of CA-based cropping systems (Prasad and Power, 1991). Crop residues improve soil health and moisture conservation and can also pose problems for weed seed germination by obstructing sunlight. The germination response of weeds to residue depends on the quantity, position (vertical and below- or above-ground weed seeds), allelopathic potential of the residues, and weed biology (Chauhan et al., 2006). With this in mind an experiment was established to evaluate different crop establishment methods for wheat crop with respect to wheat and rice yield, weed dynamics, nutrient uptake and profitability for long term sustainability of rice-wheat rotation on clay loam soil of eastern India.

2. Materials and methods

2.1. Experimental site

The experiment was conducted at the research farm (25˚34′6.33″N, 83˚59′0.18″ E and 63 m above sea level) of the Farm Science Centre, Buxar of ICAR Research Complex for Eastern Region, Bihar, India during the 2012-13 and 2013-14 seasons. Prior to experimental establishment, the field was under a puddled transplanting rice and conventional till wheat system since 2006. The soil was clay loam in texture, slightly alkaline in reaction (pH 7.6) with 0.43% organic carbon (Walkley and Black, 1934), 128 kg ha^{-1} alkaline $KMnO_4$ oxdizable N (Subbiah and Asija, 1956), 17.2 kg ha^{-1} Olsen-P and 168.3 kg ha^{-1} ammonium acetate extractable-K.

The climate of the area is semi-arid subtropical, characterized by very hot summers and cool winters. The hottest months are May and June, when the maximum temperature reaches 45–46 ◦C, whereas during the coldest months of December and January the temperature often drops below 5 ◦C. The average annual rainfall is 1100 mm, 65–82% of which is received through the northwest monsoons during July through October. In 2012-13 the growing season total rainfall was 936 mm and in 2013-14 it was 1019 mm. The distribution of rainfall was more uniform from June to October during both years, during which 96 and 88% of the rainfall occurred in 2012-13 and 2013-14, respectively (Figure 1). In January of 2013 the wheat crop received 25 mm of rainfall while in 2014 it received 61 mm in January and 59 mm in February. The weekly mean maximum temperature ranged from 21 to 43°C with an average of 31.2°C during 2012-13, and 21 to 43°C with an average of 31.2°C during 2013-14. The weekly mean minimum temperature ranged from 4 to 35°C with an average of 18.4°C during both years.

2.2. Experiment description

The four treatments consisted of four different wheat crop establishment methods in a rice-wheat rotation as follows:

1. Wheat sown with zero-till (ZTW): The wheat crop was seeded in ZT plots at 20 cm row spacing using ZT seed-cum-fertilizer drill.
2. Wheat sown with Happy Seeder (HSW): The wheat crop was seeded in HS plots at 20 cm row spacing using a Happy Seeder machine along with fertilizer placement in single operation.
3. Wheat on raised beds (BPW): Soil was tilled using two harrowings and three ploughings (using a field cultivator) followed by one field leveling (using a wooden plank). The raised bed was prepared using a tractor-drawn bed planter along with seeding and fertilizer placement in single operation. The beds were 50 cm wide at the top, 10 cm in height, and separated by furrows 25 cm wide. Three rows of wheat were seeded on each bed at 20 cm row to row spacing.
4. Conventional till wheat (CTW): The conventional farmer practice for soil tillage involved two harrowings, three ploughings (using a field cultivator), and one field leveling (using a wooden plank). The wheat was seeded in rows 20 cm apart using a seed-cum-fertilizer drill. Each treatment was evaluated in a randomized complete block design with five replications.

Each experimental plot measured 10 m × 7.5 m (75 m^2).

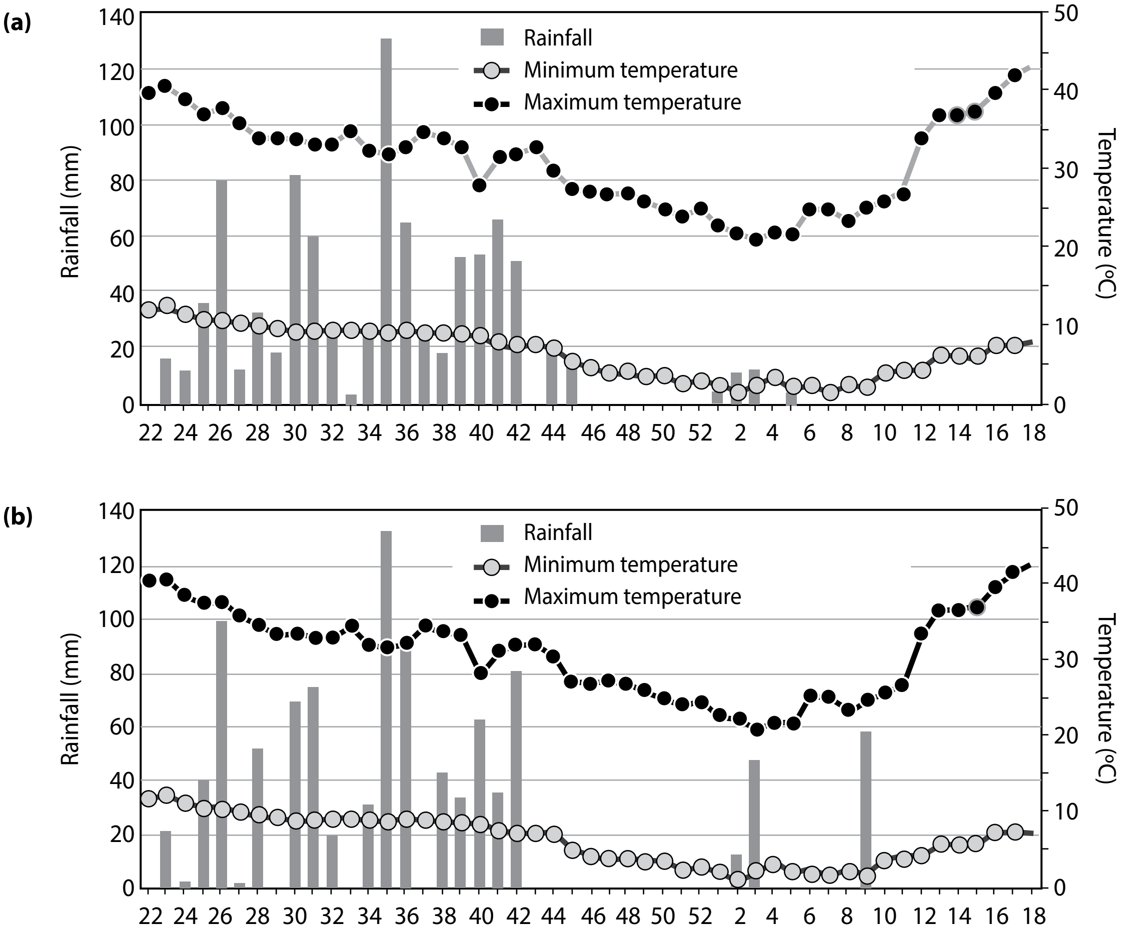


Figure 1. Weekly maximum temperature, minimum temperature and rainfall at the experimental site versus week of year for (a) 2012-13 and (b) 2013-14.

For the rice crop, the nursery was raised using 20 kg ha^{-1} seed rate (rice variety BPT 5204) in the month of June. A 25 day old nursery was transplanted in the field with spacing of 20 cm × 10 cm. Pretilachlor (0.5 kg a.i. ha^{-1}) was applied 3 days after transplanting in all the plots to control weeds in rice fields. Wheat (variety HD 2733) was seeded at 100 kg seed ha^{-1} at 20 cm row spacing in ZTW, HSW and CTW, and a seed rate of 85 kg ha^{-1} was used in furrow irrigated raised bed planted wheat (BPW). To control weeds in wheat, sulfosulfuron (33 g a.i. ha^{-1}) at 35 days after sowing was used to control grasses, sedges and broad-leaved weeds. Transplanting of rice and seeding of wheat were done on the same day in all the treatments of both years.

Both rice and wheat were harvested manually with partial residue retention: 20 cm high (ZTW and BPW) and 30 cm high (HSW) anchored rice stubbles, 20 cm high anchored wheat stubbles in all treatments except CTW. In both rice and wheat, all plots received 120 kg N, 26 kg P, and 50 kg K ha^{-1}. Half the N and all P and K were applied as basal at sowing of wheat and at transplanting of rice. In rice, the remaining half of the N was top dressed by broadcasting urea in two equal splits: one at active tillering and one at panicle initiation stage. To wheat, the remaining half of N was top dressed in two equal split doses; the first split before 1st post-sowing irrigation at crown root initiation stage and the second before 3rd irrigation at pre-flowering stage.

2.3. Crop and weed data collection

Initial plant population of wheat was determined by counting the number of plants in 1 m^2 at three locations within each plot and expressed as plants m^{-2}. Plant height of five randomly selected plants in each individual plot was measured using a meter scale from base of plant (soil surface) to apex. For biomass, plants were cut close to the ground in 0.5 m long transects at five random places within each plot. Samples were first dried in the sun and then oven-dried at 65°C until constant weight was achieved. Yield parameter counts (number of spikes/ panicles) were done in the same manner as the initial plant population. The spike length of ten randomly selected plants in each plot was measured from base of the spike to tip. The mean spike length was computed and expressed in cm. Number of grains per spike/panicle was counted in ten randomly selected plants from each plot and averaged to obtain the number of grains per spike per panicle. 1000 grains from each plot were counted and their weight was recorded (14% moisture). Grain yield was taken from a 5 m × 2 m (10 m^2) area for ZTW, HSW and CTW, and 5 m × 2.25 m (11.25 m^2) for BPT (3 beds of 75 cm) in the center of each plot and expressed in kg ha^{-1} at 12% moisture. The grain samples were subjected to analysis of N content through alkaline permanganate stem distillation microkjeldahl method, phosphorus content colorimetrically using vanadomolybdophosphoric acid yellow colour method and potassium content through flame photometrically (Jackson, 1973). Weed count, for estimating weed density at 30 and 60 days after sowing (DAS) in wheat, was recorded using a quadrat (0.5 m × 0.5 m) placed randomly at four spots in each plot. To record weed dry weight, weeds were cut at ground level, washed with tap water, sun dried, hot-air oven-dried at 75°C for 48 h, and then weighed.

2.4. Gross margin analysis

Cost of cultivation under different treatments was estimated using approved market rates for inputs as fixed by the Director, ICAR Research Complex for Eastern Region, Patna, India. Other variables included costs of seed, fertilizers, chemicals, human labor (minimum wage rate by Govt. of India), fuel for land preparation, seeding, irrigation, fertilizer application, plant protection, harvesting, and threshing, and the time (h) required per ha to complete an individual field operation. Gross returns were calculated using the support price offered by Commission for Agricultural Costs and Prices, Government of India for rice (US$224.1 and $228.8 Mg^{-1} during 2013 and 2014, respectively) and wheat (US$232.7 and $237.2 Mg^{-1} during 2013 and 2014, respectively). Net returns were calculated as the difference between gross income and total cost of production.

2.5. Data analysis

All data on weed density and weed dry matter values, yield and yield parameters of rice and wheat, and economics were analyzed as per the methodology of Gomez and Gomez (1984). Treatments were compared using the "F-test". The significant differences between treatments were compared pairwise by critical difference at 5% level of probability.

3. Results

3.1. Wheat growth and yield

Wheat growth attributes were significantly influenced by crop establishment methods (Table 1). Plant density was the highest in HSW and the lowest in CTW, while BPW and ZTW had intermediate plant density in both growing seasons. Plant density varied from 115 plants m^{-2} (CTW in 2012-13) to 144 plants m^{-2} (HSW in 2013-14). Plant density under HSW was 21 and 23% higher than CTW during 2012-13 and 2013-14, respectively

Plant height varied from 81 to 92 cm (Table 1). CTW had the lowest plant height in both growing seasons; in 2012-13 CTW plant height was significantly lower than all other treatments, but in 2013-14 the difference was only significant compared to HSW, which had the tallest plants. In both years HSW resulted in the highest biomass, which was statistically higher for all other treatments during both growing seasons except BPW in 2013-14. Biomass was lowest under CTW (813 and 817 g m^{-2}) for both years.

The number of spikes per m^2 was significantly influenced by treatment (Table 1). The HSW produced the highest number of spikes compared to all treatments except BPW, while CTW produced the lowest number of spikes during both growing seasons. The HSW recorded significantly higher spike

Table 1. Effect of crop establishment methods on growth of wheat.

	Plants m^{-2} at 20 DAS		Plant height (cm)		Biomass (g m^{-2})		Spikes m^{-2}	
	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14
ZTW	125	128	88	88	836	849	319	354
HSW	139	144	92	92	894	905	381	384
BPW	131	133	90	90	850	884	370	379
CTW	115	117	81	86	813	817	311	317
LSD	6	7	5	5	39	53	20	21

ZTW: zero till wheat, HSW: Happy Seeder planted wheat, BPW: bed planted wheat, CTW: conventional till wheat, DAS: days after sowing, LSD: least significant difference at P=0.05

length compared to BPW, ZTW and CTW (Table 2). The BPW had the second highest spike length and was on par with ZTW. Shortest spike length was recorded under CTW. The number of grains per spike varied from 36 to 45 and was the highest under HSW followed by BPW and ZTW. The 1000 grain weight was also influenced by treatments in both growing seasons and was the lowest with CTW and the highest under HSW (Table 2).

Crop establishment method significantly affected wheat grain yield in both growing seasons (Table 2). Wheat yield was the highest under HSW followed by BPW, the lowest being under CTW. Grain yield under HSW was 3.4 and 4.1% higher than under BPW, 8.3 and 11.0% higher than under ZTW and 20.8 and 24.46% higher than under CTW in 2012-13 and 2013-14, respectively.

3.2. Nutrient content

The nutrient content in the grain was affected by wheat establishment method (Table 3). The N content varied from 1.67 to 1.85% and was an average of 0.2% higher in 2013-14 compared to 2012-13. The P and K content in grain were the same in both growing seasons. HSW recorded higher content of N, P and K in grain than other crop establishment methods. The lowest nutrient content was associated with CTW.

3.3. Weeds

Nine weed species were identified and grouped into grass (*Phalaris minor, Avena ludoviciana* and *Cynodon dactylon*), sedge (*Cyperus rotundus*) and broad leaved weeds (*Rumex retroflexus, Chenopodium album, Mililotus alba, Anagalis arvensis* and *Vicia sativa*). *Phalaris minor* (grass) and *Chenopodium album* and *Rumex retroflexus* (broad leaf) weeds were the dominant weed species in all crop establishment methods (Figure 2). Weed density was higher in the first year as compared to the second in all treatments at both stages, except the density of *Cynodon dactylon, Rumex retroflexus, Chenopodium album.* Over all treatments, total weed density at 30 DAS was 29 to 16% lower during the second year compared to the first (Table 4). Total weed density at 60 DAS was 8.2%, 7.1% and 2.9% higher in the second year in HSW, BPW and CTW, respectively while it was 4% lower in ZTW compared to the first growing season.

Density of grasses, sedges and broad-leaf weeds was significantly influenced by crop establishment method. Density of all weed species was higher in CTW over other treatments. HSW exhibited the lowest weed densities of all species at both the stages followed by BPW and ZTW, with CTW exhibiting the highest density of weed flora (Figure 2). Similarly total weed dry weight was the lowest in HSW and the highest in CTW (Table 4).

Table 2. Effect of crop establishment methods on yield attributes of wheat.

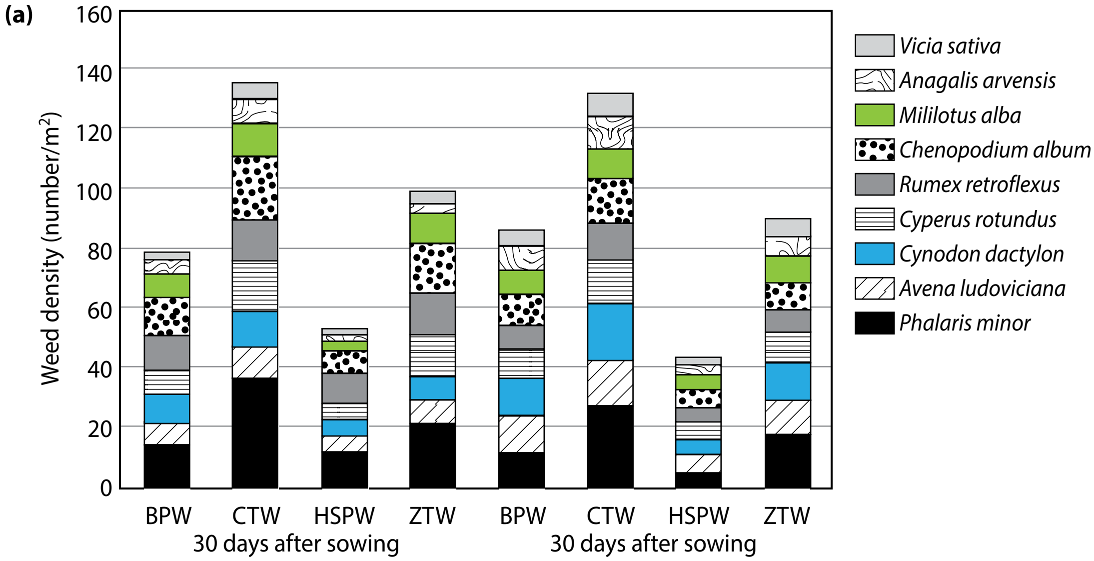
	Spike length (cm)		Grains spike^{-1}		1000 grain weight (g)		Grain yield (Mg ha^{-1})	
	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14
ZTW	8.5	8.4	41	40	38	38	3.99	4.12
HSW	9.5	9.5	43	45	43	41	4.35	4.63
BPW	8.8	8.9	42	42	40	40	4.20	4.44
CTW	7.5	7.5	36	36	37	36	3.61	3.72
LSD	0.5	0.5	2	3	2	2	0.19	0.25

ZTW: zero till wheat, HSW: Happy Seeder planted wheat, BPW: bed planted wheat, CTW: conventional till wheat, LSD: least significant difference at P=0.05

Table 3. Effect of crop establishment methods on nutrient content in wheat.

	N content in grain (%)		P content in grain (%)		K content in grain (%)	
	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14
ZTW	1.75	1.77	0.26	0.26	0.52	0.52
HSW	1.83	1.85	0.28	0.28	0.59	0.59
BPW	1.78	1.80	0.26	0.27	0.56	0.56
CTW	1.67	1.69	0.25	0.25	0.52	0.52
LSD	0.04	0.02	0.02	0.01	0.02	0.02

ZTW: zero till wheat, HSW: Happy Seeder planted wheat, BPW: bed planted wheat,
CTW: conventional till wheat, LSD: least significant difference at P=0.05



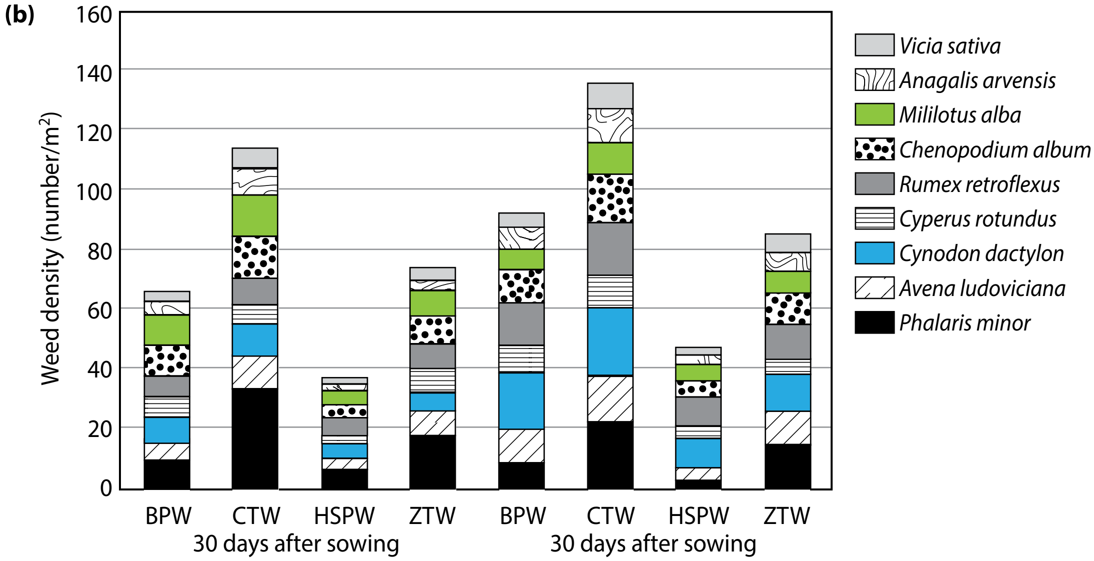


Figure 2. Weed density of nine evaluated species as affected by management practice and sampling date in (a) 2012-13 and (b) 2013-14. ZTW: zero till wheat, HSW: Happy Seeder planted wheat, BPW: bed planted wheat, CTW: conventional till wheat, DAS: days after sowing.

Table 4. Total weed density and weed dry weight in wheat.

	Total weed density (No. m^{-2})				Total weed dry weight (g m^{-2})			
	2013		2014		2013		2014	
	30 DAS	60 DAS	30 DAS	60 DAS	30 DAS	60 DAS	30 DAS	60 DAS
ZTW	99	90	74	86	21	29	15	28
HSW	53	44	37	48	11	14	8	16
BPW	79	86	66	93	17	28	14	30
CTW	136	132	114	136	28	43	23	45
LSD	10	3	6	6	2	1	2	2

ZTW: zero till wheat, HSW: Happy Seeder planted wheat, BPW: bed planted wheat, CTW: conventional till wheat, DAS: days after sowing, LSD: least significant difference at P=0.05.

3.4. Rice growth and yield

Rice grain yields were higher in the second year compared to the first and the increase varied from 1.53 to 5.49% depending on the treatment. HSW registered the highest rice yield with values 7, 16 and 30% higher than BPT, ZTW and CTW, respectively. Wheat crop establishment method significantly affected biomass, number of panicles, number of grains per panicle, and grain yield of the subsequent rice crop (Table 5). The HSW treatment produced higher rice biomass than other treatments. Number of panicles varied from 347 to 438 panicles m^{-2}. HSW produced 25.8 % more panicles compared to CTW. Grains per panicle were highest under HSW, followed by BPW. Lower values of biomass, panicle number and grains per panicle were associated with CTW. The 1000 grain weight of rice was not affected by wheat establishment method.

3.5. Economics

The maximum cost of wheat production was recorded under CTW followed by BPW and HSW, whereas the minimum cost of production was observed with ZTW (Table 6). Gross return and net return of wheat were significantly influenced by crop establishment method. Gross return was higher with HSW followed by BPW. The gross return was lowest in CTW. The net return form wheat production across treatments and years ranged from 385 to 676 USD ha^{-1}. In general, the net return was higher in HSW and lower in CTW.

The maximum gross and net return of rice was observed with HSW followed by BPW and ZTW (Table 7). The CTW resulted in significantly lower gross and net return than the other treatments.

Table 5. Effect of crop establishment methods on growth and yield attributes of rice.

	Biomass (g m^{-2})		Panicles m^{-2}		Grains panicle^{-1}		1000 grain weight (g)		Grain yield (Mg ha^{-1})	
	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14
ZTW	986	1008	373	378	127	128	21.1	21.2	3.93	4.03
HSW	1102	1111	436	438	150	151	22.0	21.6	4.58	4.65
BPW	1100	1106	403	413	142	144	21.4	21.3	4.24	4.39
CTW	874	932	347	348	108	116	21.5	21.7	3.46	3.65
LSD	55.9	24.1	23.0	21.5	12.8	10.9	NS	NS	0.15	0.20

ZTW: zero till wheat, HSW: Happy Seeder planted wheat, BPW: bed planted wheat, CTW: conventional till wheat, LSD: least significant difference at P=0.05.

Table 6. Effect of crop establishment methods on economics of wheat.

	Cost of production (US$ ha^{-1})		Gross return (US$ ha^{-1})		Net return (US$ ha^{-1})	
	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14
ZTW	406	408	928	977	522	569
HSW	422	423	1012	1099	591	676
BPW	440	441	978	1054	538	613
CTW	455	456	841	882	386	426
LSD		43	59	43	59	

ZTW: zero till wheat, HSW: Happy Seeder planted wheat, BPW: bed planted wheat, CTW: conventional till wheat, LSD: least significant difference at P=0.05.

Table 7. Effect of crop establishment methods on economics of rice.

	Cost of production (US$ ha^{-1})		Gross return (US$ ha^{-1})		Net return (US$ ha^{-1})	
	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14
ZTW	434	457	880	922	446	465
HSW	434	457	1026	1065	592	607
BPW	434	457	951	1005	518	548
CTW	434	457	775	835	341	378
LSD		34	45	34	45	

ZTW: zero till wheat, HSW: Happy Seeder planted wheat, BPW: bed planted wheat, CTW: conventional till wheat, LSD: least significant difference at P=0.05.

4. Discussion

The higher plant density in HSW followed by BPW and ZTW is ascribed to the correct placement of seed and fertilizer, and the favorable environment provided by the residue cover for seed germination and protection from abiotic and biotic stresses (Singh et al., 2013). The higher plant height and biomass with HSW might be due to the uniform residue retention on the soil surface reducing evaporative losses, buffering the soil moisture and temperature as well as canopy temperature. Higher plant density along with lower weed pressure both could contribute to increased plant performance of HSW crop establishment. We attribute the CTW's shorter plant height and lower biomass to higher weed incidence, which may have resulted in greater competition for nutrient, waster, space and light (Jat et al., 2009).

Yield attributes are the function of growth and development during the vegetative phase of the plant. Higher value of spikes m^{-2}, spike length and grains per spike in HSW compared to BPW and ZTW are perhaps due to better partitioning of photosynthates from source to sink as a result of better growth due to more favorable growing condition in this treatment. Lower spikes m^{-2}, spike length and grains per spike under CTW might be due to lower plant density and biomass production. Wheat yield was higher in the second season in all the treatments, which may be due to the rain in January and February of the second season, which provided a more favorable environment to produce a higher number of shoots and biomass. Higher wheat yields in HSW and BPW are ascribed to more productive tillers, higher biomass, higher yield attributes, enhanced fertilizer and water use efficiencies and to a significant reduction in weed population; particularly *Phalaris minor, Cyperus rotundus* and *Chenopodium album*. Similar results were also reported by Erenstein et al. (2008).

The increase in nutrient content in wheat grain in the second growing season might be due to decomposition of residue improving the fertility level of the soil, resulting in more uptake of nutrients. HSW recorded higher content of N, P and K in grain over other treatments. Probable reasons for higher nutrient content in grain are residue on soil surface preserving the plant nutrients as well as improved physical, chemical and biological properties of the soil. Continuous adoption of intensive tillage practices in CTW may destroy the soil properties resulting in lower nutrient contents.

The density of *Phalaris minor, Cyperus rotundus* and *Chenopodium album* was lower at both the stages in HSW. This might be due to the high residue load at the surface and minimum disturbance of soil. Chokkar et al. (2007) reported that density of weeds, especially *Phalaris minor* was higher in CTW. Density of weed flora and dry weight were lower under HSW, which we ascribed to residue cover on the surface and minimum disturbance of soil which reduced germination. Singh et al. (2013) reported that the Happy Seeder reduced the weed population 28% over conventional tillage. Higher plant density also reduced the weed density. Increased tillage practiced under CTW provides the environment for more weed germination. Erenstein et al. (2008) also reported that conservation tillage reduced the germination and stunted the growth of *P. minor*.

Higher plant dry weight, number of panicles, number of grains per panicle, and grain yield of rice under HSW might be due to residue retention on soil surface and decomposition which improve the soil physical, chemical and biological properties, which in turn improve water and nutrient use. Intensive tillage in CTW plots destroys the soil structure which lowers both yield and yield attributes (Conant et al., 2007; Fernandez et al., 2007).

The short term positive effects of reduced/zero tillage and improved management practices observed on yield were translated into more favorable economics. Tillage and crop establishment methods account for a major part of total crop production costs. The lower production cost in HSW and ZTW compared to CTW was due to eliminating tillage costs, lower establishment cost, and less use of fuel and labor. CTW had a higher production cost due to higher tillage and establishment costs and higher fuel and labor costs. The higher Net Benefit from HSW and BPW is ascribed to higher grain yield, lower cost of production, reduced weed growth and population, enhanced fertilizer and water-use efficiency (Ozpinar, 2006; Erenstein et al., 2008). The higher benefit cost ratio from HSW and BPW is ascribed to higher grain yield and lower cost of production than CT. The lower benefit cost ratio under CTW might be due to higher cultivation cost in addition to provision of favorable environment for weeds which heavily dominated the wheat crop causing reduction in grain yield compared to HSW and BPW (Chhokar et al., 2007). The higher net return and benefit cost ratio in HSW was due to higher production of grain yield over other methods.

5. Conclusion

This two year study showed that wheat seeded using the Happy Seeder resulted in higher net returns for both wheat and rice production compared to other wheat establishment methods. The lowest net returns in both crops were obtained in conventionally tilled wheat. The main factors contributing to increased net returns with Happy Seeder wheat were the reduced production costs as well as increased yield, which was due to improved plant population and reduced weed pressure compared to the other tested methods.

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Chapter 4. Quick reference manual for the operation of a multicrop/multipurpose zero till planter for two wheel tractors

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1. General Introduction and Precautions

The presented document aims to provide general guidelines for the correct operation of a multicrop/multipurpose machine, to be used for agricultural purposes, driven by a two wheel tractor power source. The implement offers a mechanized solution for sustainable intensification of small holder production systems and provides flexibility for farmers to implement conservation agriculture practices or similar resource conservation farming techniques.

What follows is a general overview of the machine, together with a quick guide to its main components and accessories. Moreover, guidelines for correct usage of the implement, depending on the farmer's needs, are given in combination with configuration recommendations and common caveats.

General warnings and precautions are as follows:

- When transporting the equipment off-field, make sure the working tool is disengaged using the clutch mechanism
- Accessories, like coulters, should have sufficient clearance, at least 20 cm from the ground
- We recommend a general operating speed of 3-4 km hr^{-1}
- Bolts and nuts should be tight to avoid play of components
- Sharp edged tools like cutting discs should be handled with care to avoid injury

This manual should be used in conjunction with the operation manual for the power source; in this case a 2 wheel tractor (2WT) of 15 hp is recommended. A complete description of uses and safety concerns associated with 2WTs is beyond the scope of this manual. This manual is intended for quick reference and educational purposes; it should not be considered a full and in-depth operation manual.

2. Purpose of the Device

The machine presented is an implement that can be hooked up behind a 2WT to be used during agricultural activities. The equipment can be used for planting seed, applying fertilizer, and forming/reforming ridges. A variety of seeds can be handled with this machine (maize, wheat, soybean), depending on the seed plate used. Due to its functional flexibility and broad utility this tool is considered a multipurpose/multicrop zero till planter.

3. Description of the Equipment

Figure 1 presents the complete assembly of the implement, configured with the accessories for planting. Other configurations (fertilizer application, bed reshaping, ridge making) will be described in later sections.

In Figure 1 the main components shown are the tool mounting bar, the seed and fertilizer hoppers and the seeding/fertilizing train, which consist of a coulter followed by a furrow opener with attached compaction wheels. Lastly, the depth control wheels are located at the back of the implement (which must be in a high position for off-field transportation).

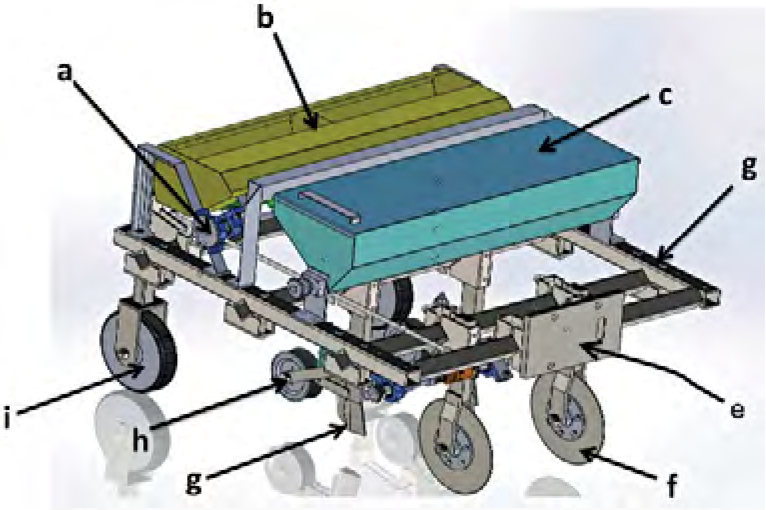

Figure 1. Parts of Zero till planter. a) Drive sprockets b) Seed hopper c) Fertiliser hopper d) Toolbar mounting e) Hitch f) Cutting disc/coulter g) Furrow opener h) Soil compacting wheel i) Depth control wheel/transport wheel.

3.1. Tool Bar Chassis

The tool bar chassis is made up of a hitch mechanism, a mounting toolbar, and transport wheels. This assembly is hinged on the power source; in this case a 2WT. Figure 2 shows an assembly of the tool bar chassis mounted/hitched on the power source.

3.1.1. Tool mounting bars

The tool mounting bars consist of two bars where tools are mounted. Various implements can be mounted on the tool bars (ridgers, coulters, openers, etc.) and they are placed by bolting them onto the toolbar using braces. Tools can be mounted on either the front or back tool bar, depending on the sequence requirements of the operations, *i.e.* coulters can be mounted at the front bar while furrow openers for seed and fertilizer are placed at the rear tool bar.

Figure 2. Tool mounting unit. a) Tool mounting bars b) Hitching point c) Power source.

The tool bar is a square mounted at a 45 degree angle (diamond shape). This configuration eliminates possible rotation of tools mounted about the bar when engaged in soil.

3.1.2. Power source

The planter is mounted by bolting a hitch on a 2WT, usually with a power of 15-18HP. The tractor provides power for system traction and to drive the seed and fertilizer metering devices.

3.1.3. Power transmission and traction

With the 2WT operational, power is transferred from the 2WT wheel axle to drive the planter (seed and fertilizer metering plates) using chains and sprockets (Figure 3).

The seed metering plate is connected to an axle on which a gear is mounted. This gear is connected to a chain driven by the 2WT wheel axle. The speed of rotation of the seed meter depends on the gear reduction ratio between the sprocket on the 2WT and the one on the seed hopper axle. The auger on the fertilizer hopper is also driven the same way as the seed metering plate.

3.2. Toolbar components and accessories

3.2.1. Seed and Fertilizer Hoppers

The planter cum fertilizer applicator has two hoppers, one for seed and the other for fertilizer. The seed hopper inclination angle is adjustable to meet the flow requirements of seed and better plate filling. For information on how to adjust this angle, please see section 4.2.3. The hoppers are compartmentalized to avoid jamming and to help distribute the seed and fertilizer more uniformly. Seeds and fertilizers are directed to the furrows on the ground by flexible transparent hoses or tubes.

3.2.2. Coulter/cutting disc

The coulters or cutting discs cut residue on the field and prepare a slot in the soil ahead of the furrow opener. Equipment can become blocked from incomplete residue cutting on soft soils. This is more prone to occur

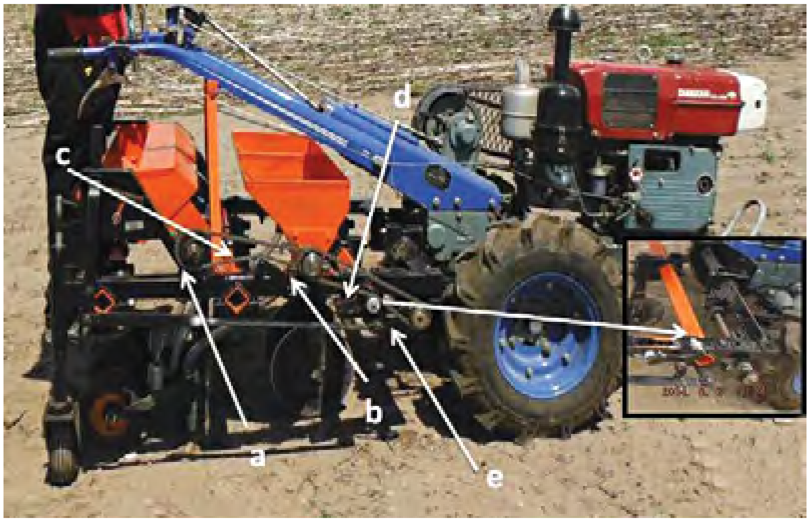

Figure 3. Power transmission system. a) Seed metering axle and sprocket b) Fertilizer auger axle/sprocket c) Seed metering chain drive d) Auger sprocket chain drive e) Driver sprocket connected to drive wheel sprocket through a chain.

when residues are wet, and thus tend to bend rather than to be cut. As such, efficiency of cutting depends on the following points:

- Soil conditions: influence of texture, resistance to penetration
- Residue conditions: resistance to cutting, humidity, quantity and management
- Seeder weight and dynamics
- Cutting disc size, shape and profile

For good results it is recommended:

- To work during the warmest hours of the day (after 10 am) or in conditions when residue is dry
- Operate when soil moisture is at the point of soils being friable
- Incline the disc so that it attacks the mulch at an angle[1]
- Use fluted cutting discs that trap the soil before cutting

Inefficient cutting leads to an accumulation of residues between the different parts of the seeder and results in irregular seed and fertilizer placement.

3.2.3. Furrow openers

A furrow opener is shown in Figure 4.

Furrow openers are used to make an opening into the soil for seed and/or fertilizer deposition. In order to minimize soil disturbance, furrow openers are smooth and thin, a design commonly referred to as an inverted-T furrow opener. Their depth can be controlled first by adjusting the furrow opener on its mounting, and if needed by depth control wheels (see Section 4.1).

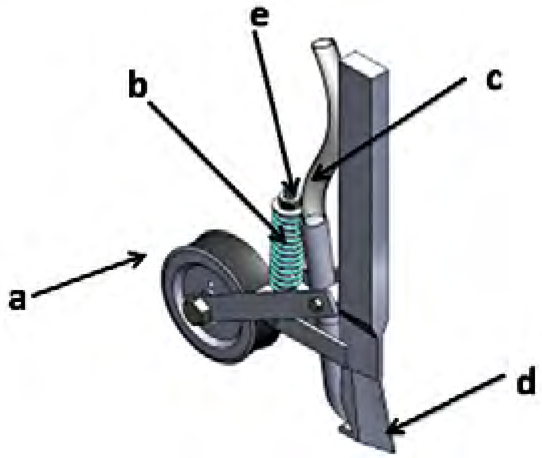

Figure 4. Furrow opener assembly. a) Press wheel b) Spring c) Seed depositing tube d) Furrow opener e) Bolt for spring adjustments.

3.2.4. Spring loaded soil press wheels

Press wheels are mounted on the furrow opener as a single assembly, shown in Fig. 4a. They compact the soil after seed has been placed to ensure good seed to soil contact. If there is poor soil compaction, load the spring by turning the bolts in the clockwise direction (Fig. 4e). Avoid over-compaction as this will result in delayed or poor germination. Wet soil is easily compacted and care must be taken not to over-pack the soil, as this makes it difficult for seedling roots to penetrate the soil. In dry soil conditions, extra closing force may be needed.

4. Set-up instructions and operation

4.1. Off-field transportation

Wheels attached on the back of toolbar (Fig. 1i) have two functions, namely transportation and adjusting of reaching depth of mounted accessories like the furrow openers.

During transportation, the depth control wheel should be in the lowest position possible to ensure that coulters and the furrow openers do not touch the ground or hit stones on the ground. This can be done by adjusting the height using the screw mountings; clockwise screwing will raise the tool bar and lower the depth control wheel (Figure 5). Counterclockwise screwing will lower the tool bar and hence increase the operation depth of the implements mounted to the toolbar. During transportation, disengage the power transmission from the tractor wheel axle to the equipment using the clutch. To disengage, move the clutch forward (Figure 5).

Figure 5. Adjusting transportation/penetration depth wheels and clutch system. a) Transportation wheels b) Clutch handle.

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[1] NOTE: in order to avoid more than minimal tillage, this angle of the cutting disc should be held at a minimum

Depending on the desired operation, different accessories and configurations can be chosen. Possible configurations include planting and fertilizer application on single row flat-field, double row flat-field, single row narrow bed and double row narrow bed[2]. Other operations include forming or reforming narrow bed ridges or irrigation furrows.

4.2. Field Operations

4.2.1. Configurations for planting

During planting, the coulter cuts biomass in front of the furrow opener. The furrow opener then opens a furrow and drops seeds at a spacing determined by the seed plate and sprocket combination selected. It also opens a furrow and drops fertilizer in the opening. The press wheel closes the furrow.

(i) Single row flat field

The cutting disc and furrow opener are all aligned at the center of the tool bar (Fig. 6). It is recommended to mark guidelines with chalk prior to planting.

(ii) Single row narrow bed

The configuration is the same as that in the previous section (see Section 4.2.1(i)).

(iii) Double row-flat field

Seed and fertilizer application will happen in two rows on a flat field. Distance between the two furrow openers depends on inter-row spacing requirements of a particular crop (*i.e.* for wheat this is usually 250 mm). The configuration for this operation is shown in Figure 6 (c and d). A coulter is mounted in-front and in-line with each furrow opener. Again, chalk guidelines are recommended for planting on the flat.

(iv) Double row-narrow bed

Seeding and fertilizer application will here be performed in two rows on a narrow bed. The same configuration as that of double row-flat field is adopted, although the distance between furrows can be adjusted depending on the width of the bed. The wheels of the tractor should follow the furrows.

(v) Wide beds

Due to the limited working width of the 2WT, wide beds greater than 750 mm are not recommended as wheels will compact the edges of the bed. Excessive compaction will reduce seed emergence and hence yield.

4.2.2. Configurations for ridging and reshaping of beds

(i) Ridging

Two ridgers can be mounted on the tool bar adjacent to one another to form narrow ridges. Single faced opposite ridgers are required for this purpose, *i.e* one throwing soil to the left and the other to the right forming a narrow heap of soil in a strip.

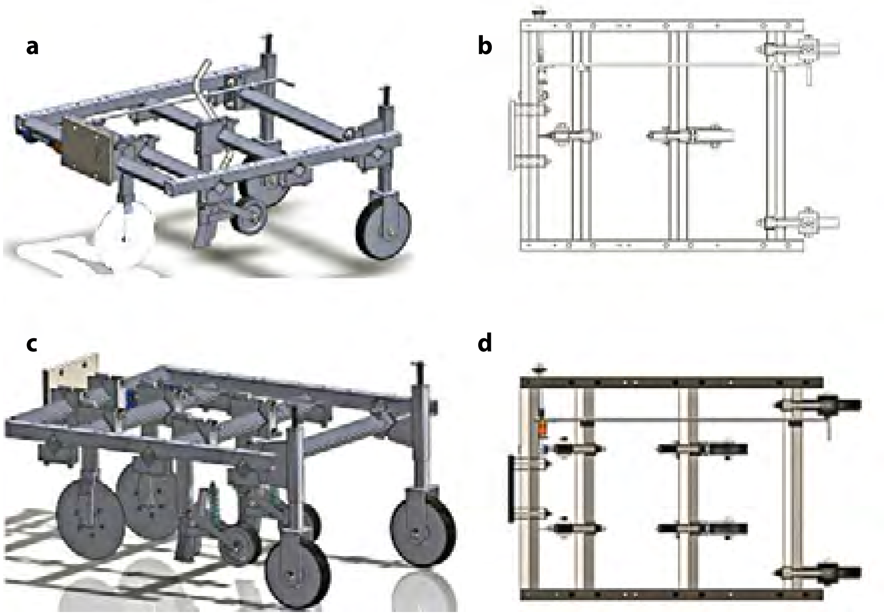

Figure 6. a) Single row plating configuration b) Schematic top view for single row planting configuration c) Double row planting configuration d) Schematic top view for double row planting configuration.

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[2] Narrow bed is referred to as a raised planting area, usually with 75-80 cm between furrows.

(ii) Reshaping beds

Ridgers can be mounted on the toolbar to follow in the previously formed furrows and with a coulter in front of them to reform ridges. This configuration is shown in Figure 7, while Figure 8 shows field operation.

4.2.3. Setting preparation before field operation

In order to avoid problems during time sensitive planting, equipment should be repaired at the end of every planting season, and prepared before the start of the new one.

(i) In the workshop

Check the operation of the seed metering devices and replace worn parts. Adjust the seed metering devices using the current year's seed to match seed size and shape. Check, adjust, and lubricate chains, sprockets, bearings, and fittings. Replace worn ones. Adjust or replace the seed-furrow opener disks and other ground engaging components. Properly inflate tractors wheels.

(ii) In the field before planting season

Blind plant (or use old seed) for a short distance to check operation. Check residue cutting and handling, check penetration to desired seeding depth, evaluate seed-to-soil contact, and evaluate seed distribution. Adjust the hoppers' inclination, operation speeds and sprocket combination if seed or fertilizer rates do not match the desired rates. Adjust coulter to improve residue cutting. Add weight as needed on the front of the two wheel tractor to reduce turning effort, keeping drive wheels in firm contact with the ground to avoid slippage if needed. To improve traction on the wheels of the 2WT, water can be added to the wheels.

In order to increase the working width of the system, tractor wheel separation can be increased to the desired value by adjusting the position of wheels on the wheel axle. Variable seed spacing is a sign of discontinuity in seed dropping mainly caused by inappropriate angle of seed hopper.

Figure 9 shows different scenarios when seeding. Figure 9a shows correct deposition, 9b shows what happens if the seed plates do not fill up properly. If the scenario in Figure 9b occurs, adjust the seed hopper by loosening the bolts fastening the seed

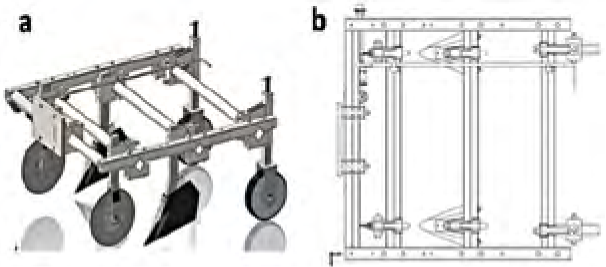

Figure 7. a) Configuration for ridging b) Schematic top view for ridging configuration.

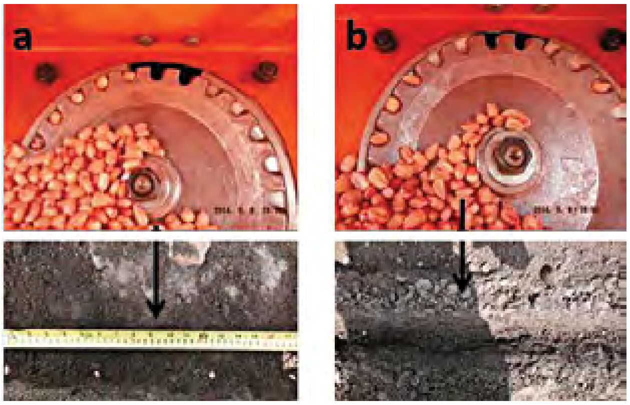

Figure 9. a) All seed is dropping, desired scenario, even spacing of seeds is seen after opening soil to check b) Some seed remains attached to the holes of the seed plate causing uneven seed spacing, seen after opening up the soil to investigate seed spacing.

Figure 8. On-field configuration for ridging. a) Full lateral view b) Ridgers in action c) Reshaping the beds.

hopper to the mounting and moving the seed to the left. If seeds are smaller and tend to clog the discharge hole, move the hopper to the right as shown in the arrows in Figure 10 below. For small seeds, continuous pouring of seed is required; therefore shift the seed hopper to the left. For large seeds, shift the seed hopper to the right.

4.2.4. General Operation

Adjustments may be needed as soil and residue conditions change. Continuously monitor planter performance and make adjustments as conditions dictate. Since the planter system must handle and cut the residue, allow the residue to dry and become crisp before planting. These conditions aid in the cutting and handling of the residue. The weight of the planter is essential. The recommended operating speed is 6-10 mph although higher operating speed assists in residue flow.

(i) In the field during planting season, especially when changing fields

Check residue cutting and handling. Leave more residue over the row as the weather warms up to reduce seedbed drying. Check planting depth and seed-to-soil contact. Lower pressure in wet soils that are easily compacted. Slow down to improve seed placement uniformity. Check seed spacing for proper population.

(ii) Checking seed depth

There is a strong tendency to plant much deeper than intended. Excessive depth delays germination and reduced stands.

(iii) Check for seeds on the ground

Seeds on the soil surface might be a result of shallow operation depth, thus operating depth should be adjusted.

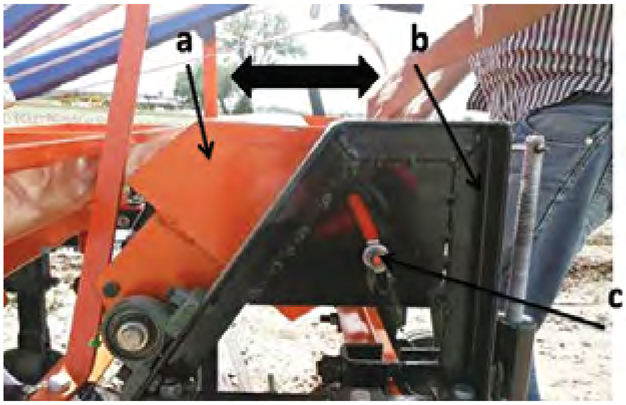

Figure 10. Adjusting the tilt angle of seed hopper.
a) Seed hopper b) Seed hopper supporting frame c) Bolt for adjusting inclination of the seed hopper.

(iv) Check for hairpinning

When operating a planter system in heavy residue, residue may be pushed in the seed furrow (hairpinning), reducing seed-to-soil contact and slowing or reducing germination. Make sure the cutting angle on the coulter is correct (coulter depth should not exceed one-third the coulter radius) and the cutting edge is sharp. The hairpin effect is minimized when seeding units operate on a firm soil, and when residue is dry and crisp. Simply waiting until a little later in the day, when residue is drier, may greatly improve the operation of the planter system.

(v) Erratic Operation

Any time the operation of the planter causes the metering unit to jerk, variable seed placement will occur. Adjust all elements of planter operation for smooth performance. Observe and adjust planting speed to match ground conditions.

(vi) Riding platform

For less soil engaging operations, the operator can stand on the foot rest at the rear as shown in Figure 11. For operations requiring deep penetration of soil and when going too deep, the traction required might exceed tractor capacities (*i.e.* 15 hp). In this case, walking behind the planter might lighten the work.

4.3. Calibration

Calibration is done to achieve the desired seed/fertilizer application rate. Calibration is done for both large seeds and small seeds.

4.3.1. Calibration for large grains (maize, beans, etc.)

Large grains are calibrated by counting the number of seeds in a certain linear distance. For example, count the number of seeds deposited in the middle 2 m of a 10 m stretch.

Formula Example

Desired seeding density of maize is 80 000 seeds ha^{-1} and each row is 0.75 m wide.

Calibration area = 2 m × 0.75 m = 1.5 m^2

Number of seeds required in 1.5 m^2 calibration area

$= 80{,}000 \text{ seeds/ha} \times (1/10{,}000 \text{ m}^2/\text{ha}) \times 1.5 \text{ m}^2$

$= 12 \text{ seeds}$

Therefore adjust the system so that it drops 12 seeds in every 2 m evaluated.

4.3.2. Calibration for small grains (sorghum, wheat, millet, etc.)

Small grains are calibrated using kg ha^{-1}. Attach plastic bags at the spout where seeds are discharged and walk 50 m. Weigh the bags.

Figure 11. Foot placement options. a) On foot rest b) Walk behind.

Formula Example
Desired wheat planting density is 100 kg ha^{-1}
80 cm beds with 2 rows, row spacing = 30 cm
Calibration area = 50 m × 0.80 m/2rows = 20 m^2
By proportion: 100 kg/ha × 20 m^2/ 10,000 m^2/ha = 0.200 kg seed per bag

4.3.3. Calibration for fertilizer application
Calculating the composition of the fertilizer mix (N-P-K)

Create a mixture with your specifications. Calibrate in similar fashion to small grains (using plastic bags and weighing amount of fertilizer dropped in a certain distance).

4.3.4. Making adjustments for correct calibration
Several parameters will govern seed application rate, including seed metering plate, angle of inclination of seed hopper and sprocket size of seed metering plate drive shaft. Since this is a multi-purpose/multicrop planting unit, setting requirements differ from crop to crop. However, the following adjustments are made to increase seed rate:

- Use a small sprocket size of seed metering plate drive shaft
- Select a seed plate appropriate to the seed to be planted which can apply in multiple rows. Some seed plates plant 2 or more rows at the same time and some plant in one row.
- Incline the seed hopper forward, so that seeds can easily cover seed metering plate, this works well for small seeds as it allows continuous flow of seed.

The opposite adjustments can be done to reduce seed application rate:

- Use a large diameter sprocket size of seed metering plate drive shaft
- Select a seed plate appropriate to the seed to be planted which can minimum number of rows in a single pass. Some seed plates plant 2 or more rows at the same time and some plant in one row.
- Incline the seed hopper backward. This allows seed to be picked up by plate singly and works well for large seeds.

5. Maintenance

5.1. Furrow opener

For the furrow opener, check for wear. No-till planting or planting in conditions of compacted soil will greatly increase furrow opener wear and necessitate frequent inspection. When the furrow opener is worn, replace it.

5.2. Servicing seeding equipment

- Clean the planter inside and out. This should be done before the unit is sheltered. Check for old seed left in the hoppers, mouse nests, spiders, insects, build-up from seed coatings and anything else that may interfere with the operation of the seed meter or seed drop tubes.
- Check and replace all worn out parts.
- Ensure that coulters and openers are aligned accurately.
- Replace worn seals and check trueness of fit.
- Adjust or replace worn openers.
- Check condition of sprocket teeth.
- Replace worn chains. Lubricate or replace chain links.
- Inflate tires to the correct inflation pressure.

Chapter 5. Impact of irrigation levels and sowing dates on the marginal analysis of crop water production functions and yield response factor of wheat (*Triticum aestivum* L.) in Eastern India

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Abstract

A field experiment was conducted for three consecutive years (2009-10, 2010-11 and 2011-12) to study the effects of water deficit on yield, water productivity, and water use efficiency (WUE) of wheat in rice-wheat cropping systems in West Bengal of Eastern India. The experiment included 18 treatment combinations of two sowing dates (DOS), three irrigation levels, and three wheat cultivars tested in a split-split-plot design with three replications. The DOS each year was 25 November (D_1) and 20 December (D_2). Irrigation treatments were: one irrigation at crown root initiation (CRI; I_1), irrigation at CRI, tillering and boot stage (I_2), and irrigations at CRI, tillering, jointing, boot stage and milk stages (I_3). Wheat cultivars were PBW-343 (V_1), K- 307 (V_2) and RSP- 561 (V_3). The seasonal evapotranspiration (SET) was higher under timely sown conditions (D_1) compared to late (D_2). Maximum SET values were obtained with five irrigations (I_3) while the highest WUE was obtained under one irrigation (I_1) applied at CRI. Timely sowing of wheat (D_1) resulted in 9–10 % higher WUE compared to late sowing (D_2). Based on the evapotranspiration production function, the minimum ET under D_1 was estimated to be 115 mm which could produce 1757 kg ha^{-1} grain yield, while for D_2 the minimum ET was 152 mm that could produce 1992 kg ha^{-1} yield with maximum WUE. For maximum yield and ET scenarios, D_2 produced 13% less yield combined with an 8% reduction in ET compared to D_1. The lowest values of EWP were obtained under I_1 and D_2. The quadratic evapotranspiration production function for different irrigation levels revealed that a maximum ET of 444 mm could provide a maximum yield of 4934 kg ha^{-1} while under dryland or rainfed situations where emphasis in on WUE, ET levels of 177 mm could provide a minimum yield of 2499 kg ha^{-1}. Higher values of EWP under delayed sowing indicated that there is scope to increase the yield and WUE of the crop through better irrigation scheduling.

Keywords**:** Water use efficiency, seasonal evapotranspiration, marginal water use efficiency, elasticity of water productivity, yield response factor.

Abbreviations: ET: evapotransporation; CWP: crop water function; ETPF: evapotranspiration production function; SET: Seasonal Evapotranspiration; WUE: Water Use Efficiency; MWUE: Marginal Water Use Efficiency; EWP: Elasticity of Water Productivity; Ky: Yield response factor.

Introduction

Wheat (*Triticum aestivum* L.) is sown as either a rainfed or irrigated crop after the withdrawal of monsoon in India. Shifting rainfall patterns often delay wheat planting because of high soil moisture content during the early part of November. When planting is delayed, less water may be available for the crop and thus increased water use efficiency (WUE) is desirable. Therefore irrigation management plays a vital role for achieving yield targets.

Due to a restricted water supply there is a growing interest in reduced irrigation, which may result in mild stress but could have minimal effects on yield. However, under conditions of mild water stress, reduced irrigation can lead to increased yields rather than maximizing yield per unit of water input. Understanding the effect of water stress on yield is essential for planning a suitable irrigation strategy for wheat. Additionally, matching sowing time with evapotranspiration (ET) demand will help to achieve maximum yield.

Wheat is quite sensitive to water stress, and therefore needs frequent irrigation for optimal growth and yield (Alderfasi and Nielsen, 2001). Under normal conditions, 4-6 irrigations are recommended for optimum wheat production in India (Singh, 1991). Both yield and quality will likely suffer from insufficient or improperly timed irrigation. Crop water production (CWP) functions describe the relationship of crop yield to varying levels of water input and are useful for water management applications (Liu et al., 2002). The CWP function expresses the relationship between yield and the total amount of water evapotranspired (Doorenbos and Kassam, 1979; Yaron and Bresler, 1983; English and Raja, 1996). In general, change in crop yield can mainly be attributed to different transpiration rates (Olesen et al., 2000). The evapotranspiration production function (ETPF) describes the relationship between yield and seasonal ET. It can take different forms and the empirical coefficients will vary with climate, crop type, variety, irrigation, soil texture, fertiliser and tillage methods. Many researchers have deduced a linear relationship between yield and ET (Singh, 1981; Mogensen et al., 1985; Steiner et al., 1985; Musick et al., 1994; Zhang and Oweis, 1999); whereas Kang et al. (2002) showed that the relationship between ET and yield or WUE can be best described by quadratic functions. A non-linear crop response may occur when increased irrigation frequency results in increased ET without a corresponding increase in yield. In field studies with wheat, barley, and sugarcane Gulati and Murty (1979) reported yield to be a quadratic function of ET. Another component known as the yield response factor (Ky) describes the relationship between ET deficit (expressed in relative terms of maximum yield, Y_{max}, and corresponding maximum ET, ET_{max}) and corresponding yield reduction (Doorenbos and Kassam, 1979) as follows in Equation 1:

$$Ky = \frac{1-\dfrac{Y}{Y_{max}}}{1-\dfrac{ET}{ET_{max}}} \qquad \text{eq. (1)}$$

Crops having Ky<1 are more tolerant to water deficit and have a smaller yield reduction at constant ET compared to crops with Ky>1 where the crops are more sensitive to water deficit and have larger yield reductions with reduced water use due to stress (Doorenbos and Kassam, 1979).

The objective of this study was to determine the relationship between ET and wheat grain yield for varying irrigation levels and timing under different sowing dates in West Bengal of Eastern India. Although limited studies for linear ETPFs are available, studies relating Ky with yield, ET and WUE with respect to a quadratic yield and ET relationship for this region are not available. It is also necessary to understand the elasticity in water productivity with respect to a non-linear ETPF and the effect of irrigation levels and dates of sowing on the marginal analysis of crop water production functions. These relationships will assist in the determination of marginal WUE (MWUE) and elasticity of water production, which will allow researchers and producers to determine optimal combinations for a given planting scenario in a given area.

Materials and methods

The experiment was carried out at the District Seed Farm of the Bidhan Chandra Krishi Viswavidyalaya, Kalyani (22^{0} 59′ N, 88^{0} 25′ E, 9 m above sea level), West Bengal of Eastern India. The study site had a medium type land topography in a tropical humid climate. The study site soil was a deep alluvial with a sandy loam texture (Typic Fluvaquent) with good drainage capacity. It was low in N, P and K content and had neutral pH. The hydro-physical and chemical properties of the soil are presented in Table 1. The field experiments were conducted during the winter seasons

Table 1a. Bulk density and soil water holding capacity properties.

	Soil depth (mm)			
	0 – 150	150 - 300	300 - 450	450 – 600
Soil water retained (m^3 m^{-3})				
0.01 MPa	0.3	0.28	0.26	0.26
1.5 MPa	0.12	0.09	0.08	0.07
Bulk density (g cm^{-3})	1.41	1.46	1.51	1.52

Table 1b. Mechanical composition and chemical properties.

	Mechanical composition			Chemical properties					
	Sand	Silt	Clay	Organic C	Total N	Available N	Available P_2O_5	Available K_2O	Soil pH
Units	%	%	%	%	%	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	
Values	48.5	30	21.5	0.54	0.053	227.65	19.72	218.96	7.1

(November-April) of 2009-10, 2010-11 and 2011-12. The mean annual rainfall is 1457 mm (average of 30 years), 90% of which is received between June and September. The rainfall received during the crop growth period of wheat was 45.2, 153.1 and 112.8 mm for 2009-10, 2010-11 and 2011-12 respectively. During the first two study years 83 and 86% of the rainfall occurred during maturity, while during the third year 61% of the rainfall occurred during vegetative growth. The minimum (January) and maximum (April) monthly average temperatures were 16.5–18.4 °C and 23.3–26.7 °C, respectively. The cumulative monthly pan evaporation was minimal during December and maximal during April (Figure 1).

The experiment was comprised of 18 treatment combinations with two dates of sowing, three irrigation levels, and three wheat cultivars. The design was a split-split-plot randomized complete block design with three replications. The dates of sowing each year were 25 November (D_1) and 20 December (D_2). Irrigation treatments were as follows: I_1 - one irrigation at crown root initiation (CRI) 20-25 days after sowing (DAS); I_2 - three irrigations with one at CRI, one at tillering (45-50 DAS), and one at boot stage (80-85 DAS); I_3 - five total irrigations with one at CRI, one at tillering, one at jointing (65-70 DAS), one at boot stage, and one at milk stage (100-105 DAS). Three wheat cultivars PBW-343 (V_1), K-307 (V_2) and RSP-561 (V_3) were assigned to the sub-sub plots. Plots measured 16.56 m^2 (2.07m × 8m). Wheat was planted with row spacing of 23 cm. All plots were fertilized with 150:60:40 kg nitrogen (N), P_2O_5 and K_2O per ha. Grain yield was recorded from the net plot harvest and the yield components were recorded from a subsample of 50 cm rows in each replication. Seasonal ET was estimated using the water balance approach,

$$ET = P + I + C - DP - R - \Delta S \qquad \text{eq. (2)}$$

where P is the precipitation; I is irrigation; C is capillary contribution; DP is deep percolation; R is runoff and ΔS is the change in soil water storage. Since the depth of groundwater was very low, contribution through capillary rise was assumed negligible. We observed negligible changes in soil moisture storage below 60 cm soil depth, so we considered deep percolation negligible. We assumed no runoff from fields. Soil moisture extraction from 0–15, 15–30 and 30–45 cm soil depths was measured gravimetrically and computed according to Eqn. 2:

$$\left[\sum_{i=1}^{n} \frac{M_{bi}-M_{ei}}{100}\right] \times BD_i \times D_i \qquad \text{eq. (3)}$$

where, M_{bi} is the soil moisture percentage before irrigation; M_{ei} is the soil moisture percentage after irrigation; n is the number of soil layers considered in root zone depth (D_i) and BD_i is the bulk density of i^{th} soil layer.

Factors other than water were considered non-limiting. Therefore, yield and ET were both considered functions of water availability. ETPF was derived from the quadratic relationship between yield and seasonal ET represented as:

$$Y = a + b\,ET + c\,ET^2 \qquad \text{eq. (3)}$$

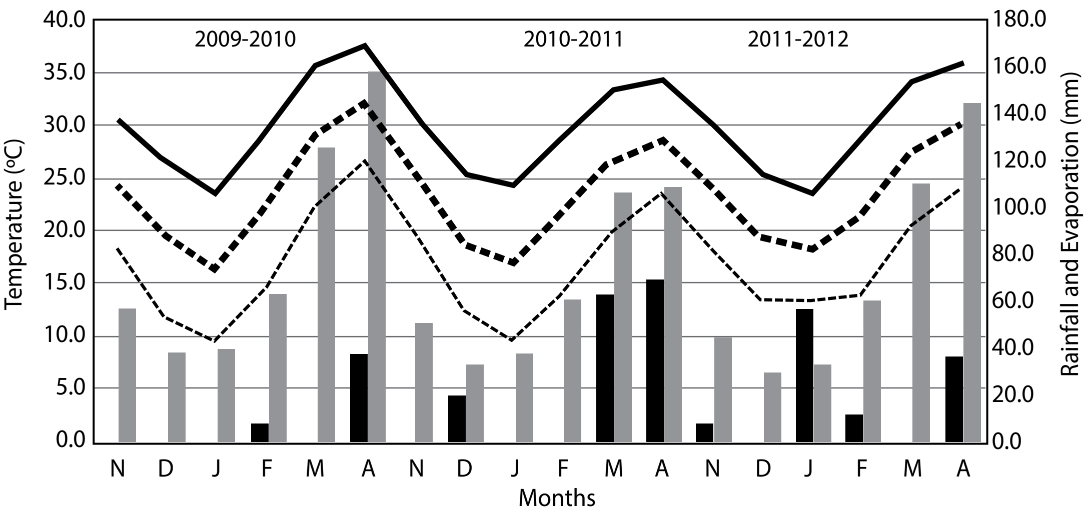

Figure 1. Weather during the growing seasons of wheat during 2009 to 2012.

In the case of quadratic functions, both the intercept (a) and quadratic coefficient (c) are generally negative (Liu et al., 2002). In economics, elasticity is a measure of how responsive an economic variable is to a change in another. This can be quantified as the ratio of the change in one variable to the change in another variable, when the latter variable has a causal influence on the former. Thus the ratio of MWUE to WUE can be viewed as the elasticity of water productivity (EWP), which provides a means to compare the relative change in yield with the relative change in ET (Liu et al., 2002):

$$EWP = \frac{MWUE}{WUE} = \frac{dY/Y}{dET/ET} \qquad \text{eq. (4)}$$

The elasticity is not constant for the entire production function. Thus Liu et al. (2002) proposed the WUE, MWUE and EWP to be as follows:

$$WUE = \frac{a}{ET} + \mathrm{b} + (c \times ET) \qquad \text{eq. (5)}$$

$$\mathrm{MWUE = b + (2 \times c \times ET)} \qquad \text{eq. (6)}$$

$$EWP = \frac{(b \times ET) + (2 \times c \times ET)}{(\mathrm{a} + b \times ET) + (c \times ET)} \qquad \text{eq. (7)}$$

MWUE will decrease linearly with increasing ET. Under such situations the yield response factor as defined by Doorenbos and Kassam (1979) can be represented as:

$$Ky = \frac{(-c \times ET^2)}{Y_{max}} \qquad \text{eq. (8)}$$

where $\mathrm{Y_{max}}$ is the maximum yield obtained. Significant effects were identified by analyses of variance (SAS 9.3) using PROC MIXED holding replication, irrigation, and variety as fixed effects. Replication by variety interactions were considered random effects. Effects were considered significant if $p<0.05$ unless otherwise stated. Means and standard errors of the means were obtained using PROC MEANS. Multiple pairwise means separation tests were conducted using the Tukey Honestly Significant Difference test at the 95% confidence level with the %PDMIX800 macro (Saxton, 1998). Regression relationships were determined using the data analysis tool pack of Microsoft -Excel.

Results

3.1. Response of seasonal evapotranspiration to different irrigation levels and sowing dates

Seasonal evapotranspiration (SET) was affected by treatment combination, results presented in Table 2. The SET values were closely related to the amounts of rainfall registered during the three cropping seasons. Under I_2 the SET values ranged between 230–254 mm and 215–245 mm for D_1 and D_2 sown crops respectively. I_3 SET values varied between 320–334 mm and 295-305 mm for D_1 and D_2 sown crops respectively. During the three cropping years, 2010–11 registered the smallest SET values in all irrigation treatments.

The loss of moisture through ET increased with increased levels of irrigation. The SET was 67–93 % and 23–39 % higher with five irrigations (I_3) compared to the I_1 and I_2 levels of irrigation, respectively. The SET values under the same irrigation levels but different dates of sowing were similar. The variety PBW-343 (V_1) recorded the highest SET values under D_1 sowing for increased levels of irrigations in two out of three years of experimentation followed by K-307 (V_2) and RSP-561 (V_3). However, for D_2 sowing, V_2 exhibited the maximum SET values followed by V_1 under I_2 and V_3 under I_3. For I_1 (one irrigation at CRI), V_2 recorded the maximum SET values followed by V_3, but was significantly different from V_1 irrespective of sowing dates (Table 2).

Table 2. Response of seasonal evapotranspiration (SET) under different irrigation levels, dates of sowing and varieties. Within a season, values followed by different letters are significantly different at p< 0.05 according to Tukey Honestly Significant Difference Test.

	2009 - 10		2010 – 11		2011 – 12	
SET	**D_1**	**D_2**	**D_1**	**D_2**	**D_1**	**D_2**
I_1V_1	163hi	162i	158i	158i	186f	170g
I_1V_2	180g	175g	171h	171h	186f	179fg
I_1V_3	178g	172gh	168hi	157i	176fg	190f
Mean	**174**	**170**	**166**	**162**	**183**	**180**
I_2V_1	245e	228f	234e	212f	260d	251d
I_2V_2	239e	248e	236e	234e	247d	260d
I_2V_3	243e	219f	220f	200g	255d	223e
Mean	**242**	**232**	**230**	**215**	**254**	**245**
I_3V_1	330a	301d	312bc	288d	332a	291c
I_3V_2	325ab	309cd	322ab	306c	329a	307b
I_3V_3	316bc	305d	325a	291d	340a	04bc
Mean	324	305	320	295	334	301

Date of sowing (D) – D_1, 25 November; D_2, 20 December
Irrigation (I) – I_1 1 irrigation; I_2, 3 irrigation; I_3, 5 irrigations
Variety (V) – V_1, PBW-343; V_2, K-307; V_3, RSP-561

3.2. Yield and water use efficiency

Increased application of irrigation significantly increased the yield of the crop. Lowest yields under both sowing dates were observed during 2010–11, while the highest yield was recorded during 2011–12 irrespective of irrigation level (Figure 2a). The highest yields coincided with rainfall during vegetative growth (Figure 1). For I_2 and I_3 irrigation levels, significantly higher yields were obtained under D_1 as compared to D_2. Over both dates of sowing, as compared to I_1 the I_2 irrigation scheme resulted in a yield increase of 19-31%, while I_3 resulted in yield increases of 39-48%. Delayed sowing (D_2) showed 10-13% decrease in yields for all the years of experimentation. Under D_1, I_1 and I_2 varietal difference was not significant between V_1 and V_2. However under I_3, V_1 produced significantly higher yields than V_2 and V_3. Under D_2 and equivalent irrigation treatments, yields of varieties V_1 and V_2 were similar, while V_3 produced significantly lower yields. Increasing irrigation levels led to increased SET values, with the increase depending on the

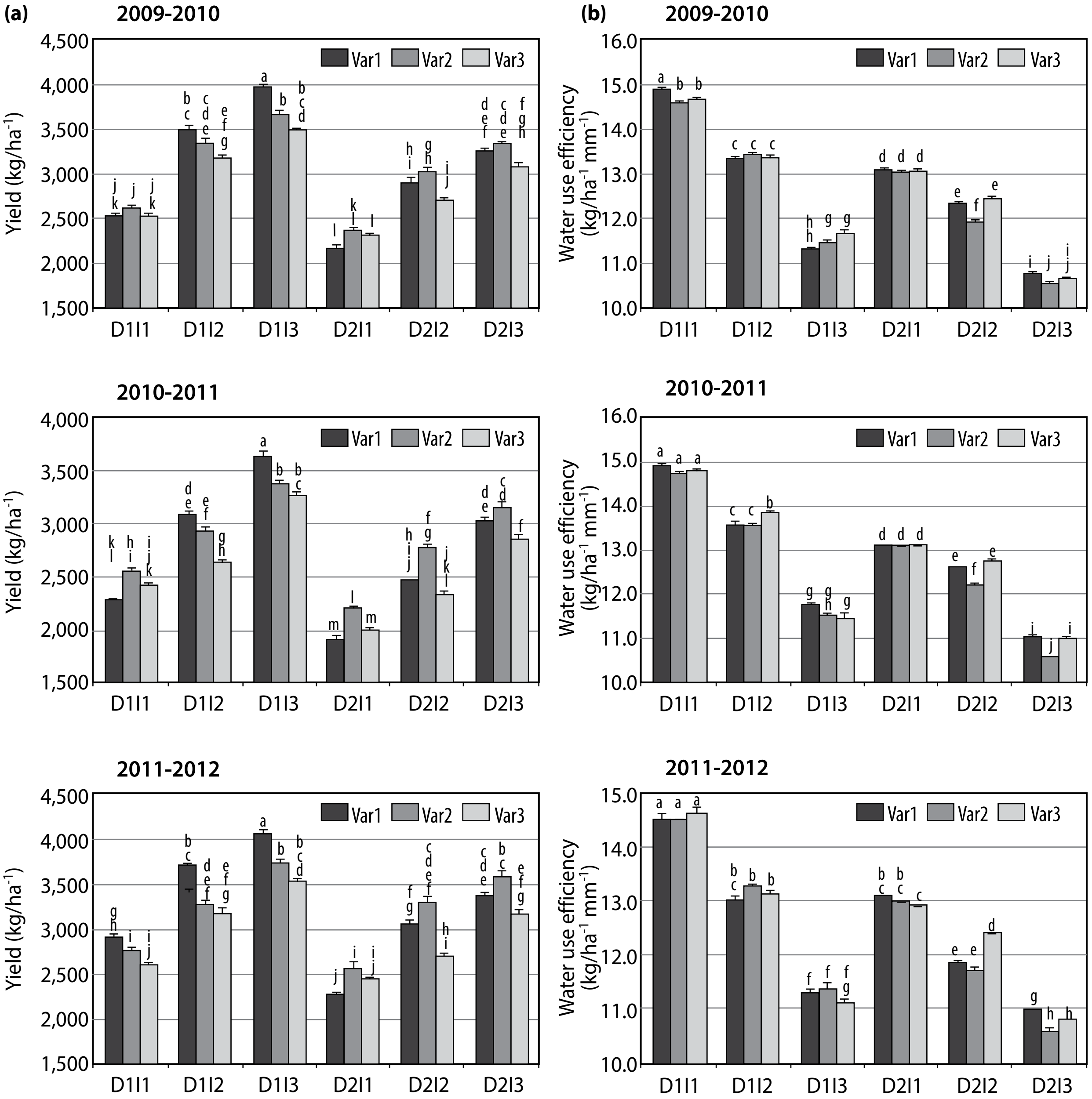

Figure 2. a.) Yield (kg ha^{-1}) and b.) water use efficiency (kg ha^{-1}mm^{-1}) of wheat varieties under different irrigation levels and dates of sowing.

Date of sowing (D); Irrigation (I); Variety (V) – as per Table 2. Within a season, values followed by different letters are significantly different at $p< 0.05$ according to Tukey Honestly Significant Difference Test.

sowing date. Under D_1, I_2 and I_3 SET values were 39 and 87% higher than I_1 and produced 26 and 43% higher yields. Under D_2 sowing I_2 and I_3 SET values were 35 and 76% higher, with a corresponding 25 and 43% increase in yield compared to I_1.

WUE varied significantly over different irrigation treatments and sowing dates but was similar among varieties. Under D_1 (25th November), I_1 had the highest WUE (14.5–14.8 kg ha^{-1} mm^{-1}) followed by I_2 (13.1–13.7 kg ha^{-1} mm^{-1}) then I_3 (11.3–11.6 kg ha^{-1} mm^{-1}) (Figure 2b). Under delayed sowing (D_2, 20th December) the WUE was lower compared to timely sowing, again with the highest values under I_1 (13.0–13.1 kg ha^{-1} mm^{-1}) followed by I_2 (12.0–12.5 kg ha^{-1} mm^{-1}) and I_3 (10.7–10.9 kg ha^{-1} mm^{-1}). When averaged over different irrigation levels for a particular date of sowing, WUE values were 9–10 % higher when sown on 25th of November compared to late sowing on 20th December. The WUE values under the D_1-I_2 treatment (13.1–13.7 kg ha^{-1} mm^{-1}) were closer to that of D_2-I_1 treatment (13.0–13.1 kg ha^{-1} mm^{-1}) although they were significantly different (Figure 2b). As compared to I_1, under D_1 WUE decreased by 7.8–9.7% for I_2 and by 16.9–22.6% for I_3. Within D_2 the reduction in WUE compared to I_1 was by 4.3–7.8 % and 16.9–18.3% under I_2 and I_3, respectively. The percent reduction in WUE under I_2 and I_3 irrigation levels was less for D_2 compared to D_1 sowing. An increase in irrigation levels from I_1 to I_2 lead to a 8-10% decrease in WUE for D_1 while the reduction was only 4-8% for D_2. Application of five irrigations (I_3) lead to a 22% reduction in WUE for D_1 while it was only 17% for D_2 when compared to I_1 (Figure 2b). The difference in WUE between D_1 and D_2 was least during 2011–12, due the rainfall during the vegetative period. The WUE showed a strong negative relationship with SET (Figure 4); the WUE decreased as SET increased and the relationship was better explained by a quadratic function.

3.3. Evapotranspirational production function and its relationship with EWP, WUE, MWUE and Ky

The relationship resulting from regression analysis between grain yield and SET over three years was best described by a quadratic function (Table 3). Grain yield gradually increased with a corresponding increase in the SET. However the grain yield response to irrigation varied considerably over different dates of sowing and irrigation levels. The relationship between yield and SET was found to be a quadratic function where 82 and 87% of the variation in yield could be explained by variation of SET under D_1 and D_2, respectively (Figure 3). In the equations obtained from regression analyses of yield and SET it was observed that yield showed a decreasing trend with increasing SET and that it was higher under D_2 compared to D_1.

For irrigation levels I_1, I_2, and I_3, 47, 74 and 51% of the variation in crop yield could be explained by variation in SET, respectively (Table 3). Although the WUE increased with decreasing irrigation, marginal water use efficiency (MWUE), was highest for I_2 and lowest for I_3 irrigation levels. For each 1 mm increase in the ET from I_1 treatment, grain yield increased 16–18 kg ha^{-1} when three irrigations (I_2) were applied. However, the MWUE declined to 15 kg ha^{-1} when five irrigations (I_3) were applied. The yield produced per unit of water input (WUE) was found to be higher under D_1 (13.2 kg $ha^{-1}mm^{-1}$) compared to D_2 (12.0 kg $ha^{-1}mm^{-1}$), however the yield increment per mm of water input (MWUE) was found to be equal (8 kg ha^{-1}) under both D_1 and D_2 sown crops.

Table 3. Crop water production functions under different irrigation regimes and dates of sowing.

Treatment	Crop water production functions	R^2	WUE (kg $ha^{-1}mm^{-1}$)	MWUE (kg $ha^{-1}mm^{-1}$)	EWP	Ky	ET_{min} (mm)	ET_{max} (mm)	Y_{min} (kg ha^{-1})	Y_{max} (kg ha^{-1})
I_1	$Y = -0.187ET^2 + 80.21ET - 5835$	0.467**	14.0	15.8	1.13	3.11	177	215	2499	2766
I_2	$Y = -0.044ET^2 + 39.03ET - 3721$	0.744**	12.8	18.2	1.43	1.75	291	444	3908	4934
I_3	$Y = -0.093ET^2 + 73.35ET - 10355$	0.508**	11.1	15.2	1.37	3.52	334	394	3766	4108
D_1	$Y = -0.028ET^2 + 21.71ET - 371.3$	0.829**	13.2	7.9	0.57	1.10	115	388	1757	3837
D_2	$Y = -0.032ET^2 + 22.84ET - 735.7$	0.875**	12.0	7.9	0.64	1.22	152	357	1992	3340

Date of sowing (D); Irrigation (I); Variety (V) WUE, Water use efficiency; MWUE, Marginal water use efficiency; EWP, Elasticity of water productivity; Ky, Yield response factor; ET_{min}, Minimum evapotranspiration; ET_{max}, Maximum evapotranspiration; Y_{min}, Minimum yield corresponding to ET_{min}; Y_{max}, Maximum yield corresponding to ET_{max}.

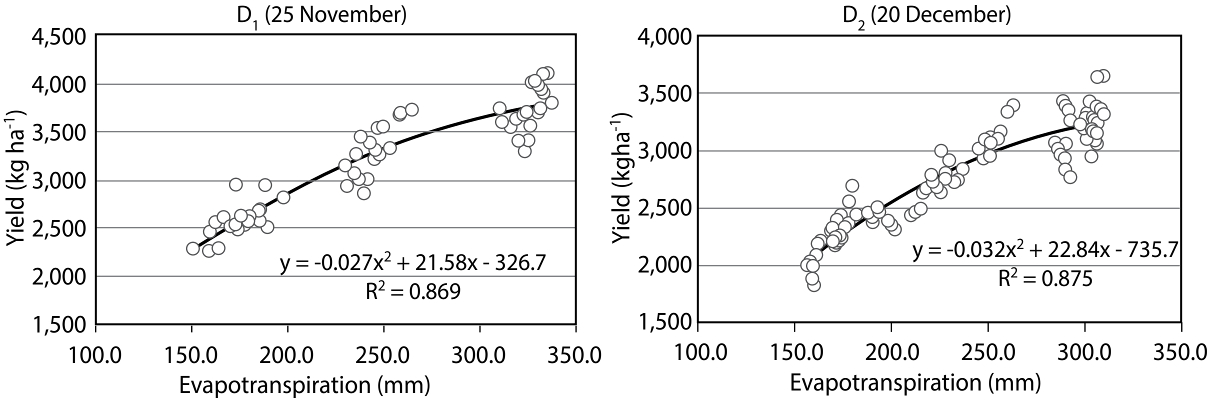

Figure 3. Relationship between yield and seasonal evapotranspiration of wheat under different dates of sowing.

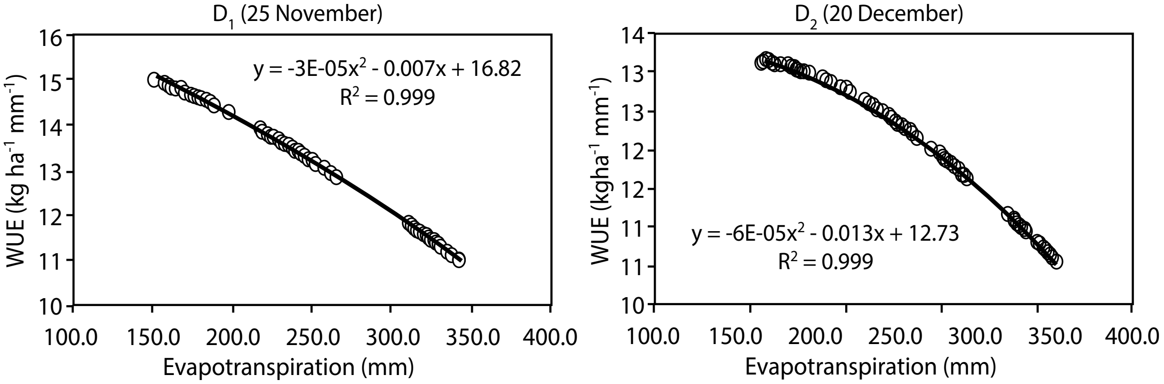

Figure 4. Relationship between water use efficiency and seasonal evapotranspiration of wheat under different dates of sowing.

The EWP function was greater than 1 averaged for each of the irrigation treatments (Table 3). Considered over different dates of sowing EWP was greater under D_2 (0.64) than D_1 (0.57) sowing. According to Doorenbos and Kassam (1979) when the EWP = 1, MWUE will be equal to WUE (Figure 5) and both will be at their maximum value, while the highest yield will be obtained when EWP = 0. Simultaneously the highest yield was obtained when the EWP = 0, regardless of dates of sowing (Figure 5). Based on the ETPF, ET_{min} under D_1 was estimated to be 115 mm which could produce 1757 kg ha^{-1} grain yield, while for D_2 ET_{min} was 151 mm which could produce 1992 kg ha^{-1} yield (Figure 5). For maximum yield scenarios, the late sown crop produced 13% less yield from 8% reduction in ET compared to timely sown crop. When considered under different irrigation levels the highest EWP was obtained under I_2 (1.43) while the lowest was under I_1 (1.13). This indicates that an ET of 443 mm could provide a maximum yield of 4934 kg ha^{-1} while under dryland or rainfed situations where emphasis in on WUE, ET levels of 177 mm could provide a minimum yield of 2499 kg ha^{-1} (Table 3).

The yield response factor (Ky) was estimated from the ETPF (Doorenbos and Kassam, 1979). In all cases Ky was higher than 1. The maximum value of Ky (3.52) was obtained under I_3 while the lowest was obtained under I_2 (1.75). It was found that Ky was 11% higher for D_2 compared to D_1. Both EWP and Ky were negatively related to SET.

Discussion

Crop production depends mainly on soil water status throughout the growing season. A high level of soil water availability usually ensures an optimal yield with maximum SET with an associated reduction in WUE. Any restriction in the supply of irrigation water is likely to induce a decrease in crop yield. When conditions are optimal, yield reaches its maximum value, as does the SET. With changes in the soil water availability there is an impact on the yield, WUE, MWUE and the EWP functions.

We saw that irrigation regimes significantly affected the SET, yield and WUE of the systems. In similar experiments, Zhang and Oweis (1999) pointed out that ET depends on the seasonal rainfall under rainfed conditions and on the combined amount of water (irrigation and rainfall) under irrigated conditions. The variation we observed in SET was likely due to the variation in canopy volume and atmospheric temperature and the reduced growing period. Lower atmospheric temperature results in a lower ET demand. The reduced atmospheric temperature was ultimately reflected in the lower seasonal ET when the crop was sown late (D_2, 20th December). Greater availability of soil water with five irrigations (I_3) compared to one (I_1) and three irrigations (I_2) increased plant growth and thereby resulted in higher amount of ET losses. The observations are in agreement with the findings of Rathore and Patel (1991) who reported that ET of wheat increased from 240 mm with 2 irrigations to 460 mm with five irrigations on clay loam soil. In earlier studies (Pal et al., 2000) reported that consumption of water varied from 272 mm with two irrigations (at CRI and boot stage) to 346 mm with four irrigations (CRI, maximum tillering, boot and milk stages).

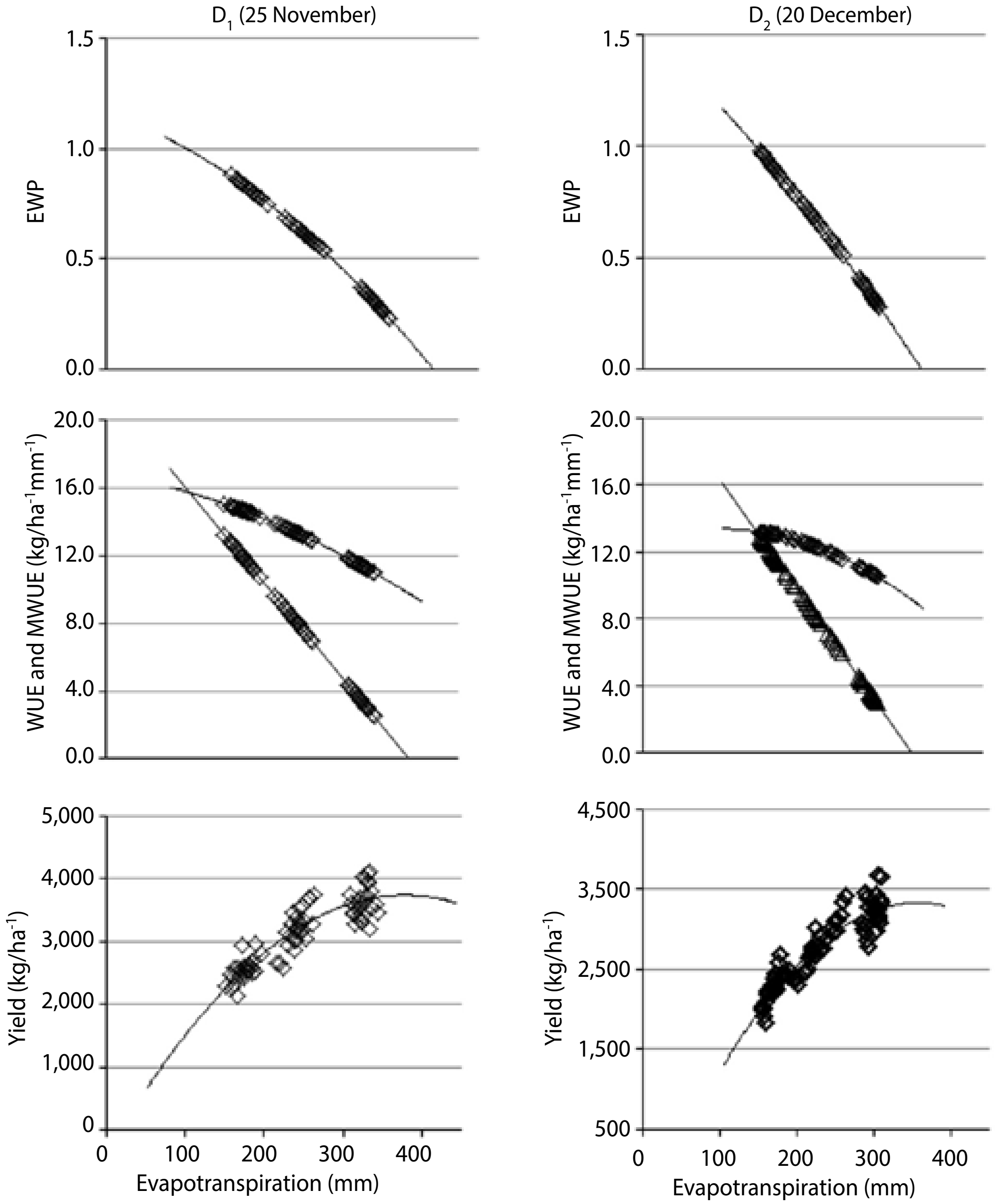

Figure 5. Relations between elasticity of water productivity (EWP), water use efficiency (WUE), marginal water use efficiency (MWUE), yield and seasonal evapotranspiration (SET) for a quadratic evapotranspiration production function (ETPF) for wheat under different dates of sowing.

With increasing irrigation levels, yield also increased but the rate of increment was not equal with each level of water added. Moreover it was observed that only 13% yield reduction occurred due to delayed sowing. The maximum yield was produced with five irrigations (I_3) irrespective of the sowing dates. It can be inferred that for wheat, beyond a certain level of yield its increment requires more water input. Other studies have found similar results (Oweis et al., 1998; Oweis et al., 2000; Zhang et al., 2004). Therefore, by controlling the dates of sowing the water requirement may be improved with the simultaneous improvement of agricultural practices (Corbeels et al., 1998; Oweis et al., 1998). Oweis and Hachum (2001) demonstrated that with staggered dates of sowing the peak demand of irrigation water during drought sensitive stages could be avoided and water productivity could be improved over a larger area.

In wheat, excessive moisture deficit reduces the time to maturity (McMaster and Wilhelm, 2003) as well as yield. Therefore, a detailed study of the ET production function is necessary to quantify the effect of altered dates of sowing and reduced water application on crop yield and WUE. Water availability is the limiting factor when ET is relatively low, while increasing ET results in an increase in both yield and WUE. Beyond optimum ET the rate of increase in yield and corresponding WUE starts to decline as ET increases further. The amount, timing and frequency of irrigation have strong impacts in WUE (Qiu et al., 2008). In fact, WUE may drop (Nasseri and Fallahi, 2007) or increase (Bandyopadhyay and Mallick, 2003) at higher irrigation levels. Results from this study also showed a negative relationship between WUE and SET. Maurya and Singh (2008) also reported a decrease in WUE with an increase in irrigation levels due to proportionately less increase in grain yield with increasing in ET. Zhang and Oweis (1999) and Steiner et al. (1985) also observed an increase in grain yield of wheat by 6.8–10.8 kg ha^{-1} per mm increase in ET. The WUE was found to decrease with increasing ET, corroborated by the quadratic nature of ETPF (Liu et al., 2002). Attaining higher yields with increasing productivity is only economical when the increased gains in crop yield are not offset by increased costs of other inputs (Oweis et al., 2004).

The WUE of D_1-I_2 and D_2-I_1 irrigation treatments were found to range within 13.0–13.7 kg ha^{-1} mm^{-1}, which showed that when less irrigation water is applied, sowing on 25th November rather than 20th December is helpful with a certain compromise in yield. Three (I_2) to five (I_3) irrigations for November sowing (D_1) gave the highest yields, while under rainfed conditions a WUE of 14.5–14.7 kg ha^{-1} mm^{-1} may be achieved with application of single irrigation (I_1). Increases in WUE are generally advocated for crops in arid and semi-arid regions. The yields of wheat were significantly higher under five irrigations (I_3), although the WUE with three irrigations (I_2) was either higher or similar to five irrigations (I_3). Higher efficiency could be achieved not through an increase in yield, but only through reduced irrigation water which may compensate for the yield reduction. Results suggested that similar wheat yields could be obtained with higher WUE through optimum use of water within different dates of sowing.

The present study also indicates that by using one irrigation at CRI (I_1) or three irrigations at CRI, tillering and boot leaf stage (I_2), yield and WUE can be improved by reducing ET. The fact that maximum ET (ET_{max}) scenarios obtained under I_2 and I_3 produced the highest yields indicates that increasing ET by 18 and 33 % from the ET_{min} of I_3 (333.7 mm), would produce 9 and 31 % higher yields respectively. Coventry et al. (2011) reported that wheat grain yield increased in a stepwise manner as additional irrigation was applied, indicating that it is possible to apply irrigation without seeing an increase in yield. Among the environmental factors, water deficit during the reproductive phase of development is the most important limiting factor for winter cereals (Blum, 2009); if reproductive development is to be successful it is essential for the plants to maintain their water regime during the generative phase, irrespective of the quantity of biomass achieved during the vegetative phase (Kato et al., 2008). This may not be possible with a single irrigation at CRI (I_1). The EWP and Ky estimated from the ETPFs for different dates of sowing and irrigation levels followed the same pattern. Both the indices achieved highest values under low WUE and high SET but produced higher yields in contrast to the lower values of EWP and Ky. From the ETPFs for dates of sowing it was observed that an increase in 30% of ET_{min} (152 mm) for D_2 would provide a yield advantage of 13% (1992 kg ha^{-1}) over D_1, obtaining the maximum WUE (Table 3). However 388 mm of SET under D_1 could produce a yield of 3837 kg ha^{-1} which was 15% higher than D_2. Thus estimation of EWP and Ky may be good indicators of the water productivity for varying levels of ET.

Conclusions

The SET was higher under timely sown condition compared to late planting. Maximum SET values were obtained with five irrigations regardless of planting date. Comparing timely sowing with late sowing under one irrigation, we saw a 39 and 87% increase in SET, which produced 26 and 43% higher yields. Under timely sown conditions the wheat WUE values varied from 14.5–14.8 kg ha^{-1} mm^{-1} for one irrigation at CRI to 11.3–11.6 kg ha^{-1} mm^{-1} under five irrigations. Under delayed sowing the values ranged from 13.0–13.1 kg ha^{-1} mm^{-1} for one irrigation to 10.7–10.9 kg ha^{-1} mm^{-1} for five irrigations. The timely sowing of wheat resulted in 9–10 % higher WUE compared to late sowing.

The EWP, Ky and WUE were affected by different soil water regimes. The maximum value of Ky (3.52) was obtained under I_3 while the lowest was obtained under I_2 (1.75). Based on the ETPF, the minimum ET under D_1 was estimated to be 115 mm which could produce 1757 kg ha^{-1} grain yield, while for D_2 the minimum ET was 152 mm that could produce 1992 kg ha^{-1} yield with maximum WUE. For maximum yield and ET scenarios, the late sown crop produced 13% less yield with an 8% reduction in ET compared to timely sown crop. The lowest values of EWP were obtained under one irrigation and under timely sown condition. The quadratic ETPF for different irrigation levels revealed that a maximum ET of 444 mm could provide a maximum yield of 4934 kg ha^{-1} while under dryland or rainfed situation where the emphasis on WUE, ET levels of 177 mm could provide a minimum yield of 2499 kg ha^{-1}. Higher values of EWP under delayed sowing indicated that there is room to increase the yield and WUE of the crop through better irrigation scheduling.

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