Journal of Plant Nutrition
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597277

Winter Wheat Grain Yield and Grain Nitrogen as Influenced by Bed and Conventional Planting Systems

To cite this Article: , 'Winter Wheat Grain Yield and Grain Nitrogen as Influenced by Bed and Conventional Planting Systems', Journal of Plant Nutrition, 30:4, 611 - 622
To link to this article: DOI: 10.1080/01904160701209378
URL: http://dx.doi.org/10.1080/01904160701209378

Journal of Plant Nutrition, 30: 611–622, 2007

ISSN: 0190-4167 print / 1532-4087 online
DOI: 10.1080/01904160701209378

Winter Wheat Grain Yield and Grain Nitrogen as Influenced by Bed and Conventional Planting Systems

K. W. Freeman, K. Girma, R. K. Teal, D. B. Arnall, A. Klatt, and W. R. Raun

Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, Oklahoma, USA

ABSTRACT

Bed planted wheat systems offer a new alternative for the traditional wheat producer to provide opportunities for crop rotation, more efficient use of water, and new techniques of nutrient management. This study was conducted to determine if planting winter wheat (*Triticum aestivum* L.) in Oklahoma on raised beds can maintain grain yields while providing more options in the cropping system. Experiments were conducted at Hennessey and Lake Carl Blackwell, Oklahoma in 2000-2001 and 2001–2002 cropping seasons. The experiments consisted of a factorial combination of two planting systems (bed and conventional), four winter wheat varieties ('Custer', Jaggar', 'Intrada' and '2174'), and three nitrogen (N) rates (0, 67, and 134 kg ha^{-1}). The experimental design was a randomized complete block with three replications. Grain yield was not statistically different between the bed and conventional planting systems for three of four site years. However, there was a trend for the conventional wheat production system to have an advantage in grain yield over the bed planting system due to difference in row configuration. For the bed system to be useful in Oklahoma, the current conventional tillage practice must be changed to reduced tillage to make use of bed plating system for conserving moisture. Also suitable planting configuration that minimizes intra-specific competition due to over-population must be addressed. Grain yield response to N rate was greater in the conventionally planted wheat versus the bed planted system.

Keywords: bed planting system, conventional planting system, dryland winter wheat

Received 11 October 2005; accepted 1 September 2006.

Address correspondence to William R. Raun, 044 North Ag Hall, Department of Plant and Soil Sciences, Oklahoma State University, OK 74078, USA. E-mail: bill.raun@okstate.edu

INTRODUCTION

Bed planting systems have been used in cultivation for centuries. Raised bed cultivation has traditionally been associated with water management issues either by providing opportunities to reduce the impact of excess water in rainfed conditions or to more efficiently deliver irrigation water in high production irrigated systems (Sayre, 2003; Cutforth and Selles, 1992). In dryland agriculture, bed planting systems are used with small dykes to trap water after a rain so the fields are able to retain this water and store moisture for future crops versus letting it runoff. Sayre (2003) noted that an important field-access advantage of bed-planting is the flexibility it allows to apply fertilizer when and where it can be most efficiently used. Fertilizer can be applied by direct placement in bands between the wheat beds without injuring the crop, and when the wheat plant can make the most efficient use of it. The majority of applied fertilizer can be delayed in a bed-planted system until the crop requirements are higher, thus it can be used more efficiently. Raised bed improved N use efficiency by 10% in a study conducted in China (Fahong et al., 2004). In another study in Mexico, Limon-Ortega et al. (2000b) reported 13.2% increase in N use efficiency due to bed planting systems compared with traditional flat bed.

According to Hobbs et al. (1998) and Smika and Unger (1986), bed-planted systems improve water distribution and efficiency. The system also provides an alternative for weed control with the ability to cultivate the furrows, and reduce lodging because the wheat plants are not exposed to soft soil conditions and more light penetrates the canopy. Additionally, bed-systems potentially allow for dramatic reductions in seeding rates. Sayre (1998) stated that the crucial first step in initiating research on bed-planted wheat was to test a wide spectrum of varieties with differing heights, tillering abilities, phenologies, and canopy architectures. Sayre (1998) went on to state that close cooperation between wheat breeders and agronomists to jointly identify and understand the proper plant type needed for optimum performance on beds was highly recommended.

Some previous research work has been reported from rainfed experiments with wheat drilled on raised beds ranging from 1.2 to 2 m spacing (Morrison and Gerik, 1983; and Gerik and Morrison, 1985). These reports consistently showed that wheat rows next to the furrow produced more heads per square meter and grains per spike than the wheat rows in the center of the bed or wheat rows flat-planted in the traditional manner. These experiments were conducted on wide beds and with only two out of eight rows next to a furrow. Consequently, the average grain yield of wheat planted on beds was not significantly different from grain yield of wheat planted on the flat. However, grain yield measured individually from the rows next to the furrow was greater than yield from rows on the flat. Conversely, Mascagni et al. (1991) noted that for grain sorghum there was an increase in grain yield, dry weight, and N uptake on crowned beds as compared to the flat seedbed. They concluded that the rows in the center of the crowned beds were where the major differences occurred. This suggested that growing conditions were more ideal on top of the crowned beds versus on the edges. Further research also showed that N uptake was higher on the crowned beds than in the flat seedbed. Alternatively, work by Sayre and Ramos (1997) has shown that narrowing beds to a width of 75–80 cm can be utilized in rainfed conditions with two to three rows drilled 15-20 cm apart on top of those beds to increase NUE, irrigation efficiency, reduce seeding rates, and allow for hand weeding as an option for weed control. Limon-Ortega et al. (2000a) attributed the reduction in seed rate in bed planting to improved emergence.

Mascagni and Sabbe (1990) attributed higher yields on wide beds (193 cm) to greater soil aeration as well as higher soil temperatures on top of the bed. This experiment investigated crowned beds, flat beds, and a conventional seedbed. There were no significant differences between seedbed types, but there was a definite trend for the crowned beds to have higher yields, NUE, and N uptake. They also stated that one possible benefit of the wide-bed planting system beyond the obvious drainage aspect was that the furrow provides controlled traffic lanes. This may be an advantage in certain production systems and in soils that tend to have compaction problems or if management practices require entering the field post-jointing.

Bed-planting can be very effective for drainage where water tables or annual rainfall result in excess surface moisture, especially after heavy rains, or even with irrigation. Under low rainfall conditions where moisture was limiting, bed planted wheat systems have demonstrated that moisture can be effectively conserved with proper residue retention and management on permanent beds (Sayre and Ramos,1997). Sweeney and Sisson (1988) reported that on poorly drained soils, wheat yields increased when grown on 75 cm raised beds. These researchers also found that soil temperature tended to be higher on the raised beds early in the growing season. Mascagni et al. (1995) observed that wheat produced on raised, wide beds may increase production efficiency and overall profitability. This raised, wide bed system may also integrate well with other crops in a rotation. While finding no grain yield advantage for raised bed wheat production by Mascagni et al. (1995), it was noted that in a situation where the field slope does not provide adequate surface drainage, bedding may be a viable management option. Also, since the use of raised beds did not significantly reduce yields, this practice may integrate into an overall production system, which involves crop rotations and potentially permanent beds.

MATERIALS AND METHODS

Field experiments were conducted at Hennessey and Lake Carl Blackwell (LCB), Oklahoma in the 2000-2001 and 2001–2002 cropping seasons. The soil at Hennessey was a Shellabarger sandy loam (fine-loamy, mixed, thermic Udic Argiustioll) while trials at Lake Carl Blackwell were located on a Port fine-silty, mixed, superactive, thermic Cumulic Haplustoll.

The experiments consisted of two planting systems (bed and conventional) as the main plot (strips). A factorial combination of four winter wheat varieties ('Custer', Jaggar', 'Intrada', and '2174') and three N rates (0, 67, and 134 kg ha^{-1}) were split over each main plot in a randomized complete block design with three replications. The beds were constructed similar to the way a producer would implement the practice in a field. Due to the importance of continuous beds, the mixing of conventionally planted plots in the same area was not implemented. Conventional and bed planted wheat employed in this experiment are shown from an early growth stage photograph at LCB (Figure 1). Main plot size was 36 m $\times$ 6.1 m while the subplot dimensions were 3.0 m $\times$ 6.1 m.

The seeding rate in both systems was 88 kg ha^{-1}. This resulted in placing more seeds per meter of row on the beds due to the fewer number of rows planted. Beds were formed in early August with a 4-row lister set up on 75 cm centers and reshaped just prior to planting in October. Nitrogen was applied as ammonium nitrate (NH_3NO_3) and incorporated with the reshaping operation prior to planting. Winter wheat was planted with a 3 m AGCO drill set with 15 cm spacing between rows. Harvest, planting, and fertilization dates are reported in Table 1. All non-experimental plot management activities were accomplished as per Oklahoma State University Extension Service recommendations for the respective sites.

Plots were harvested using a self-propelled Massey 8XP combine. The harvested area was 1.5 $\times$ 6.1 m for the bed plots. An area of 2 $\times$ 6.1 m was harvested for the conventionally planted plots. A Harvest Master yield-monitoring

Figure 1. Conventional planted wheat (left), and three rows per bed (right).

Table 1
Planting, harvest, and fertilization dates for the trials at Lake Carl Blackwell and Hennessey for the 2000–01 and 2001–02 crop cycles

	2000–2001			2001–2002		
Site	Fertilization	Planting	Harvest	Fertilization	Planting	Harvest
Lake Carl Blackwell	09/13/00	12/01/00	6/18/01	9/25/01	10/17/01	6/27/02
Hennessey	10/18/00	11/21/00	6/13/01	9/26/01	10/30/01	6/12/02

computer installed on the combine was used to record yield and grain moisture data. Grain yield from each plot was determined and a sub-sample was collected for total N analyses. Grain samples were dried in a forced air oven at 66°C, ground to pass a 140 mesh sieve (100 μm), and analyzed for total N content using a Carlo-Erba NA 1500 automated dry combustion analyzer (Schepers et al., 1989). Grain yield data were analyzed using the General Linear Model (GLM) and Mixed procedures in SAS (SAS Inst., 2001).

RESULTS AND DISCUSSION

Planting system effects on grain yield were not statistically significant except in one instance. Across years and sites, significant ($P \leq 0.05$) differences were observed among varieties (Table 2). Within each planting system, the performance of varieties was inconsistent except for the variety "Custer', which showed some consistency between systems and across sites and seasons (Table 3). Significant interactions ($P \leq 0.1$) were observed between planting system and variety at Hennessey, but no significant interactions between planting system and N rate was observed. Variety by N rate interactions was significant at Hennessey for both cropping seasons (Table 2).

One aspect of improved planting systems would be its impact on quality of dry land winter wheat. As an indictor of the effect of management systems, grain N concentration in winter wheat grain was evaluated for each treatment. Except for the variety by N rate interaction, at least one significant difference was observed for main or interaction effects considered in the study when evaluated by year and site (Table 4).

2000–2001 Season

Although not significant, the conventionally planted system out yielded the bed planted system by 133 and 335 kg ha^{-1} at Hennessey and LCB in

Table 2
Planting systems, varieties, and N rates main effect on winter wheat grain yield at Hennessey and Lake Carl Blackwell, OK in the 2000–2001 and 2001–2002 cropping seasons

		Hennessey		Lake Carl Blackwell	
		2000–2001	2001–2002	2000–2001	2001–2002
Effect		(kg ha $^{-1}$)		(kg ha $^{-1}$)	
Planting system	Bed	2125 a	2644 b	2930 a	3009 a
	Conventional	2258 a	3102 a	3265 a	3212 a
Variety	Custer	1826 c	3161 a	3033 a	3688 a
	Jagger	2335 ab	2788 b	3204 a	2596 d
	Intrada	2109 b	2488 c	3114 a	2833 c
	2174	2495 a	3057 ab	3039 a	3327 b
N-rate (kg ha^{-1})	0	1943	2931	2914	3381
	67	2184	2814	3172	3048
	134	2447	2875	3206	2903
	Linear	***	NS†	*	**
	Quadratic	NS	NS	NS	NS
Interactions					
System*Variety		P<0.1	NS	P<0.1	NS
System*N-rate		NS	NS	NS	NS
Variety*N-rate		*	**	NS	NS

Variety means in the same column followed by the same letter are not significantly different from each other at $p < 0.05$. *$p < 0.05$, **$p < 0.01$ and ***$p < 0.001$. †NS, non-significant at $p < 0.1$.

2000–2001, respectively . Combined over both planting systems at Hennessey, ‘2174’ and ‘Jagger’ had greater grain yield. ‘Custer’ was significantly lower yielding than the other varieties. While normally ‘Custer’ is a fast maturing variety, due to low March rainfall and high level of yellow rust (*Puccinia striiformis)* lower yield was recorded for this variety in 2000–2001. At LCB, no significant differences between varieties were observed when combined over both planting systems (Table 2). However, ‘Jagger’ was significantly higher yielding than ‘Custer’ in the conventionally planted system, but the varieties did not differ in grain yield in the bed planted system (Table 3). On the other hand, the interaction of system by variety at Hennessey revealed that ‘2174’ was superior in grain yield compared to ‘Custer’ in both planting systems (Table 3).

At both sites in 2000–2001, grain yield had a positive linear response to N rate (Table 2). At the Hennessey site, a variety by N rate interaction was noted. Grain yield increased linearly for all varieties with increasing N rates (Figure 2), however, the varieties ‘Custer’ and ‘Intrada’ showed a larger change

Table 3
Winter wheat mean grain yield comparisons for planting system by variety interactions at Hennessey and Lake Carl Blackwell in 2000–2001 and 2001–2002

		(kg ha $^{-1}$)			
Site	System	Custer	Jagger	Intrada	2174
			2000–2001		
Hennessey	Bed	1824 c	2180 ab	2045 bc	2453 a
	Conventional	1829 c	2491 ab	2173 b	2537 a
Lake Carl Blackwell	Bed	3041 a	2908 a	3060 a	2712 a
	Conventional	3025 b	3501 a	3167 ab	3366 ab
			2001-2002		
Hennessey	Bed	2994 a	2508 bc	2278 c	2798 ab
	Conventional	3327 a	3067 ab	2699 b	3317 a
Lake Carl Blackwell	Bed	3623 a	2410 b	2667 b	3339 a
	Conventional	3752 a	2782 c	2999 c	3315 b

Means in the same row followed by the same letter are not significantly different from each other at $p<0.05$.

in grain yield with an increase in N rate compared with varieties 'Jagger' and '2174'. The grain yield of varieties 'Custer' and 'Intrada' was <1800 kg ha^{-1} without fertilization (0 N treatment), and these two varieties performed almost equally at 67 kg ha^{-1} N rate.

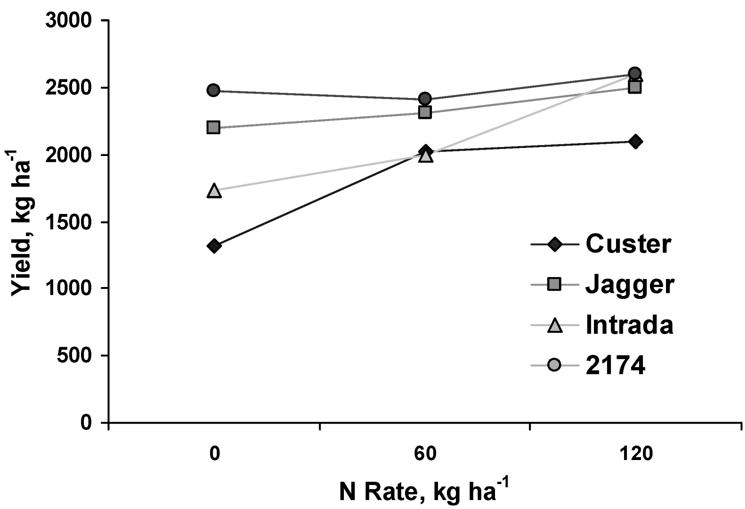

Figure 2. Grain yield response to applied N by variety interaction at Hennessey, OK in 2000–2001.

Table 4
Planting systems, varieties, and N rates main effect on grain N concentration in winter wheat at Hennessey and Lake Carl Blackwell, in the 2000-2001 and 2001–2002 cropping seasons

Effect		Hennessey 2000–2001 (g kg^{-1})	Hennessey 2001–2002 (g kg^{-1})	Lake Carl Blackwell 2000–2001 (g kg^{-1})	Lake Carl Blackwell 2001–2002 (g kg^{-1})
Planting system	Bed	25.0 a	28.1 a	25.5 a	26.1 a
	Conventional	24.6 a	23.1 b	17.1 b	25.7 a
Variety	Custer	25.1 ab	25.3 a	21.2 a	25.7 b
	Jagger	25.8 a	25.0 a	21.7 a	27.3 a
	Intrada	23.9 b	26.0 a	20.4 a	24.6 c
	2174	24.6 ab	26.2 a	22.0 a	26.2 b
N-rate (kg ha^{-1})	0	23.6	23.6	20.7	24.6
	67	24.4	26.0	21.7	26.1
	134	26.4	27.2	21.6	27.1
	Linear	***	***	NS†	***
	Quadratic	NS	NS	NS	NS
Interactions					
System*Variety		NS	NS	*	NS
System*N-rate		*	NS	NS	NS
Variety*N-rate		NS	NS	NS	NS

Variety means in the same column followed by the same letter are not significantly different from each other at the 0.05 significance level. *$p < 0.05$, **$p < 0.01$ and ***$p < 0.001$. †NS, non-significant at $p < 0.1$.

Grain N concentration was higher by 8.4 g kg^{-1} in the bed system compared to the conventional system at LCB (Table 4). It was worth noting that grain yield and N concentration were inversely related. Significant varietal difference was observed only at Hennessey, 'Jagger' resulted in higher grain N concentration compared with 'Intrada'. The interaction effect of system by variety showed that grain N concentration at LCB was 27.6 g kg^{-1} for '2174', which was 2.9 and 3.5 g kg^{-1} more than 'Custer' and 'Intrada', respectively. 'Intrada' is a hard white winter wheat with intermediate protein levels (Carver et al., 2003).

Grain N concentration linearly increased with N rate at Hennessey, however, there was no significant effect of N rate at LCB (Table 4). Likewise, the system by N rate interaction showed a similar increasing linear trend in the conventional system, but the trend was not significant in the bed system (data not shown) at Hennessey. This can be partly explained by the fact that all varieties used in the study were selected under conventional planting system.

2001–2002 Season

The planting system main effect was significant ($P \leq 0.05$) only at Hennessey in 2001–2002 cropping season. Grain yield with the conventionally planted system at this site was 467 kg ha^{-1}higher than the bed planting system (Table 2). The major reason for the relatively higher yield in the conventional planting system compared with the bed planting system could be moisture availability and intra-specific competition. In the former case since the experiment was conducted in dryland environment, flat beds allowed better moisture conservation than beds at both locations. In the latter case although in this study the seed rate per plot was the same in both systems, more seeds per meter of row were placed on the beds due to the fewer number of rows planted. Consequently this caused intra-competition among what plants that resulted in slightly lower yield in the bed planting system.

Varietal difference was also significant at both sites. 'Custer' had the highest grain yield (Table 3) at both sites while 'Intrada' and 'Jagger' had the lowest yield at Hennessey and LCB, respectively. All varieties performed better in the conventional than bed planting system at both sites except for '2174' at LCB, which performed equally in both planting systems (Table 3). This shows that '2174' is a potential variety to advance research in bed planting system as it is known to have very good straw quality (Carver et al., 2004). At Hennessey for both systems and at LCB for the bed system, higher grain yield was achieved with '2174' and 'Custer' varieties. At LCB for the conventional system 'Custer' was the highest yielding variety.

Grain yield decreased with an increase in N rate at both sites in 2001-2002, with a significant negative linear response to added N at LCB. This lack of response to applied N at LCB and Hennessey can be attributed to lodging. The varieties 'Jagger' and 'Intrada' were more adversely affected by lodging than '2174' and 'Custer' noted by their superior grain yield reported in Table 2.

The lodging problem also resulted in inconsistent grain yield among varieties at Hennessey (Figure 3). For example, 'Jagger' showed a decreasing linear trend in yield with increasing N rate while 'Custer' showed an increasing linear trend. Except for 'Intrada', the varieties had grain yields > 3000 kg ha^{-1} with no N application (Figure 3).

Grain N concentration was 5.0 g kg^{-1} more for the bed planting system at Hennessey in 2001–2002, no significant difference was observed between planting systems at LCB. As well, no differences in grain N concentrations among varieties were exhibited at the Hennessey site. Conversely at LCB, 'Jagger' was significantly higher than all other varieties, followed by 'Custer' and '2174', and 'Intrada' had the lowest grain N concentration (Table 4). At Hennessey and LCB, grain N concentration increased linearly with increasing N rates (Table 4). In 2001–2002 there were no significant interactions between planting system, varieties, and N rates (data not shown).

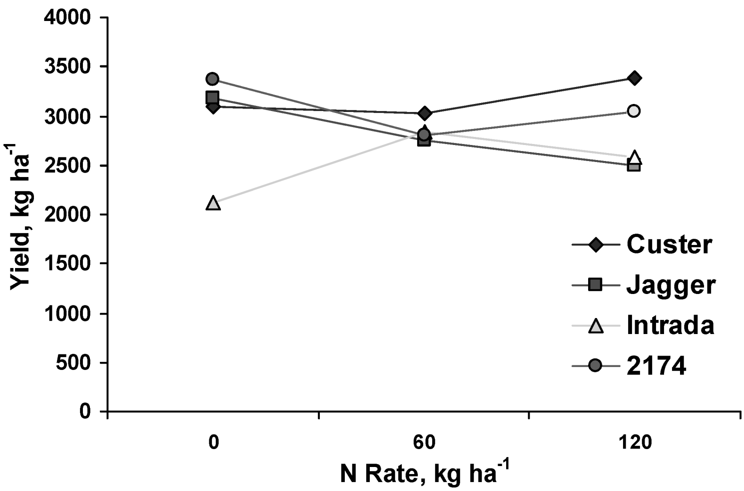

Figure 3. Grain yield response to applied N by variety interaction at Hennessey, OK in 2001–2002.

SUMMARY

The major hypothesis of this study was that 'winter wheat planted on beds does not yield less than the conventional planting system'. This hypothesis was supported for grain yield for three of four site years. However, there was a trend for the conventional wheat production system to have an advantage in grain yield over the bed planting system. Tewolde et al. (1993) drew a similar conclusion in study conducted for eight years in Texas. For the bed system to be useful in Oklahoma, the current conventional tillage practice must be changed to reduced tillage to make use of bed plating system for conserving moisture. Also suitable planting configuration that minimizes intra-specific competition due to over-population must be addressed. Grain yield response to N rate was greater in the conventionally planted wheat versus the bed planted system. The varieties tested in these trials were selected in conventional planting systems and may not be responsive to the bed planted system except for '2174'.

In all four experiments, the bed planting system consistently showed higher grain N concentrations although only two experiments were statistically significant. This clearly shows an advantage of the bed planted system over conventionally planted system in terms of grain N content of dry land winter wheat. The choice of variety however, needs to take into consideration for both grain yield and quality aspects of winter wheat. The positive linear trend due to N rates shows the need to evaluate critical fertilizer levels to adequately support the N requirements for both quality and grain yield of dry land winter wheat in bed production systems.

REFERENCES

Carver, B. F., E. G. Krenzer, R. M. Hunger, T. J. Martin, A. R. Klatt, D. R. Porter, J. Verchot, P. Rayas-Duarte, A. C. Guenzi, B. C. Martin, and G. Bai. 2003. Registration of 'Intrada' Wheat. *Crop Science* 43: 1135–1136.

Carver, B. F., E. G. Krenzer, R. M. Hunger, D. R. Porter, E. L. Smith, A. R. Klatt, J. Verchot-Lubicz, P. Rayas-Duarte, A.C. Guenzi, G. Bai, and B.C. Martin. 2004. Registration of 'Ok102' Wheat. *Crop Science* 44: 1468–1469.

Cutforth, H. W., and F. Selles. 1992. Yield and water use of paired-row versus equidistant-row seeded spring wheat in a semiarid environment. *Canadian Journal of Plant Science*. 72: 459–463.

Fahong, W., W. Xuqing, and K.D. Sayre. 2004. Comparison of conventional, flood irrigated, flat planted with furrow irrigated, raised bed planting for winter wheat in China. *Field Crops Research* 87: 35–42.

Gerik, T. J., and J. E. Morrison, Jr. 1985. Wheat performance using no-tillage with controlled wheel traffic on a clay soil. *Agronomy Journal* 77: 115–118.

Hobbs, P. R., K. D. Sayre, and J.I. Ortiz-Moasterio. 1998. Increasing wheat yields sustainably through agronomic means. NRG Paper 98-01. Mexico, D.F. Mexico:CIMMYT.

Limon-Ortega, A., K. D. Sayre, and C. A. Francis. 2000a. Wheat and maize yields in response to straw management and nitrogen under a bed planting system. *Agronomy Journal* 92: 295–302.

Limon-Ortega, A., K. D. Sayre, and C. A. Francis. 2000b. Wheat nitrogen use efficiency in a bed planting system in Northwest Mexico. *Agronomy Journal* 92: 303–308.

Mascagni, H. J. Jr., and W. E. Sabbe. 1990. Nitrogen fertilization of wheat grown on raised, wide beds. Arkansas Agric. Expt. Stn. Report Series 317. Fayetteville, AR: Arkansas Agric. Expt. Stn.

Mascagni, H. J. Jr., T. C. Keisling, and W.E. Sabbe. 1991. Nitrogen efficiency of grain sorghum grown on flat and raised seedbeds on poorly drained soil. *Journal of Plant Nutrition* 14(10): 1119–1131.

Mascagni, H. J. Jr., T. C. Keisling, W. E. Sabbe, M. May, L. R. Oliver, and E.D. Vories. 1995. Wheat production on raised beds on clayey and silt loam soils. *Communications in Soil Science and Plant Analysis* 26(3&4): 503–513.

Morrison, J. E. Jr, and T. J. Gerik. 1983. Wide beds with conservation tillage. *Journal of Soil and Water Conservation* 38: 231–232.

SAS Institute. 2001. The SAS system for windows, Version 8.02. Cary, NC: SAS Institute.

Sayre, K. D. 1998. Ensuring the use of sustainable crop management strategies by small wheat farmers in the 21st century. Wheat Special Report No. 48. Mexico, D.F.: CIMMYT.

Sayre, K. D., 2003. Raised-bed cultivation. In *Encyclopedia of Soil Science, ed.* Ratan Lal, 1–4. Taylor and Francis.

Sayre, K. D., and O. H., Moreno Ramos.1997. Applications of raised-bed planting systems to wheat. Wheat Special Report No. 31. Mexico, D.F.: CIMMYT.

Schepers, J. S., D. D. Francis, and M. T. Thompson. 1989. Simultaneous determination of total C, total N and 15 N on soil and plant material. *Communications in Soil Science and Plant Analysis* 20: 949–959.

Smika, D. E., and P. W. Unger. 1986. Effects of surface residues on soil water storage. *Advances in Soil Science* 5: 111–138.

Sweeney, D. W., and J. B. Sisson. 1988. Effect of ridge planting and N- application methods on wheat grown in somewhat poorly drained soils. *Soil and Tillage Research* 12: 187–196.

Tewolde, H., J. R. Mulkey, Jr., and R. E. Elledge, Jr. 1993. Furrow diking effects on yield of dryland grain sorghum and winter wheat. *Agronomy Journal* 85: 1217–1221.