Plant and Soil **173**: 55–65, 1995.
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Sorghum, wheat and soybean production as affected by long-term tillage, crop sequence and N fertilization

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Received 23 August 1994. Accepted in revised form 23 December 1994

Key words: crop residue quality, crop sequence, nitrogen fertilization, resource efficiency, soil productivity, tillage

Abstract

Yield decline of cereals grown in monoculture may be alleviated with alternative crop management strategies. Crop rotation and optimized tillage and fertilizer management can contribute to more sustainable food and fiber production in the long-term by increasing diversity, maintaining soil organic matter (SOM), and reducing adverse effects of excessive N application on water quality. We investigated the effects of crop sequence, tillage, and N fertilization on long-term grain production on an alluvial, silty clay loam soil in southcentral Texas. Crop sequences consisted of monoculture sorghum (*Sorghum bicolor* (L.) Moench,) wheat (*Triticum aestivum* L.), and soybean (*Glycine max* (L.) Merr), wheat/soybean double-crop, and rotation of sorghum with wheat/soybean. Grain yields tended to be lower with no tillage (NT) than with conventional tillage (CT) early in the study and became more similar after 11 years. Nitrogen fertilizer required to produce 95% of maximum sorghum yield was similar for monoculture and rotation upon initiation of the experiment and averaged 16 and 11 mg N g^{-1} grain with NT and CT, respectively. After 11 years, however, the N fertilizer requirement became similar for both tillage regimes, but was greater in monoculture (17 mg N g^{-1} grain) than in rotation (12 mg N g^{-1} grain). Crop sequences with double-cropping resulted in greater land use efficiency because similar or lower amounts of N fertilizer were required to produce equivalent grain than with less intensive monoculture systems. These more intensive crop sequences produced more stover with higher N quality primarily due to the inclusion of soybean in the rotation. Large quantities of stover that remained on the soil surface with NT led to greater SOM content, which increased the internal cycling of nutrients in this soil. In southcentral Texas, where rainfall averages nearly 1000 mm yr^{-1}, more intensive cropping of sorghum, wheat, and soybean with moderate N fertilization using reduced tillage can increase grain production and potentially decrease N losses to the environment by cycling more N into the crop-SOM system.

Introduction

Yield decline of cereals grown in monoculture decreases returns on investments, resulting in reduced profit and poor resource use efficiency (Power, 1990). Rotation of cereals with legumes can alleviate this yield decline by providing additional N to the cereal crop through legume residue decomposition (Baldock and Musgrave, 1980) and/or by altering the physical, chemical, and biological environment of the soil which affects cereal root development (Roder et al., 1989) and plant vigor (Cook, 1984; Copeland and Crookston, 1992). The contribution of additional N to the cereal has been termed a "N effect", whereas yield benefit beyond that accounted for by N has been termed a "rotation effect". Barber (1972) concluded that the rotation effect was due to improved physical condition (i.e. porosity and aggregation) of the soil after the growth of an alfalfa (*Medicago sativa* L.)/grass mixture. In contrast, however, Fahad et al. (1982) found reduced soil aggregation and porosity after soybean compared to corn (*Zea mays* L.). Biological factors that may contribute to the rotation effect with increased crop diversity include a reduction in pathogenic microorganisms (Cook, 1984), a reduction in non-pathogenic deleterious organisms (Turco et al., 1990), and the proliferation of beneficial organisms, including mycorrhizae (Jawson et al., 1993). Not all mechanisms appear to be important in all cropping systems (Whiting and Crookston, 1993). General conclusions about the nature of the rotation effect are difficult to establish because of the interactive nature of soil physical, chemical, and biological factors with the environment.

Relatively little information is available from long-term studies to compare the effect of crop sequence in contrasting tillage regimes on grain and stover production in order to assess resource use efficiency and sustainable land use. In Indiana, corn following soybean yielded greater than in monoculture with plow tillage and NT on a high organic matter soil during a 12-yr period (Griffith et al., 1988). In the same study, corn grain yield following soybean was not different than in monoculture with plow tillage, but was greater with NT on a low organic matter soil during a 7-yr period. A corn yield advantage with NT compared to plow tillage increased at a greater rate when rotated with soybean than in continuous corn on a well-drained soil in Ohio, but not on a poorly-drained soil (Dick and Van Doren, 1985). Soil-specific factors appear to be important in the consideration of rotation and tillage interactions.

We report here the effect of 11 years of continual application of tillage, crop sequence, and N fertilization practices on crop production in southcentral Texas and their potential impact on biological cycling of N in soil.

Materials and methods

Site characteristics

A long-term field experiment was initiated in the autumn of 1982 in the Brazos River floodplain in southcentral Texas (30° 32′ N, 94° 26′ W). The soil was classified as a Weswood silty clay loam (fine, mixed, thermic Fluventic Ustochrept) with a pH of 8.2 (1:2, soil:water) and contained an average of 115 g sand kg^{-1}, 452 g silt kg^{-1}, 310 g clay kg^{-1}, and 94 g $CaCO_3$ kg^{-1}. Long-term annual temperature is 20°C and rainfall is 978 mm. This soil generally contains 1% organic matter.

Crop management practices

The crop sequences consisted of monoculture sorghum, wheat, and soybean, continuous double cropping of wheat/soybean, and rotation of sorghum with wheat/soybean. The rotation sequence was duplicated so that the sorghum phase and the wheat/soybean phase occurred each year. Sorghum was planted in 1-m-wide rows at ca. 18 seeds m^{-2} in mid/late March and harvested in late July/early August. Wheat was planted in 0.2-m-wide rows at ca. 9.3 g m^{-2} in early November and harvested in mid/late May. Soybean was planted in 1-m-wide rows at ca. 23 seeds m^{-2} in early June and harvested in mid/late October. Funks DR522 safened sorghum seed was planted from 1983 to 1990, while DeKalb 56 safened sorghum seed was planted from 1991 to 1993. Northrup King Pro812 wheat was planted from 1982 to 1987, Collins from 1988 to 1992, and Karl in 1993. Ransom soybean (group VII) was planted from 1983 to 1988, Ringaround 452 (group IV) from 1989 to 1991 and Hartz 6686 (group VI) in 1992 and 1993.

All crop sequences were managed with both CT and NT. Conventional tillage operations in sorghum and soybean consisted of disking (100 to 150 mm depth) after harvest, followed by chisel-plowing (200 to 250 mm depth), a second disking, ridging prior to winter, and cultivating two to three times during early crop growth. Conventional tillage operations in wheat consisted of disking (100 to 150 mm depth) two to three times following harvest. No soil disturbance occurred under NT, except for banded fertilizer application in sorghum and planting of all crops. Sorghum stalks were shredded following harvest under both tillage regimes.

Nitrogen fertilizer (NH_4NO_3) was banded preplant in sorghum and broadcasted during late winter or early spring in wheat with none, low, medium, and high application rates. These rates were 0, 4.5, 9.0, and 13.5 g N m^{-2} in sorghum and 0, 3.4, 6.8, and 10.2 g N m^{-2} in wheat. Soybean did not receive N fertilizer in any crop sequence. Soil testing indicated that no other nutrients were limiting.

Pesticide applications in sorghum included 0.2 g a.i. m^{-2} of propazine and 0.1 g a.i. m^{-2} of metolachlor broadcasted at planting for weed control. Carbofuran at 0.06 mL m^{-2} was applied at planting for rootworm (*Diabrotica* spp.) control. Esfenvalerate at 0.02 μL m^{-2} and chlorpyrifos at 0.06 μL m^{-2} were alternated three to five times per year for control of sorghum midge (*Contarinia sorghicolo* Coquillett) during flowering.

Pesticide applications in wheat included 0.09 μL m^{-2} of diclofop-methyl broadcasted over wheat once or twice in November to December to control annual ryegrass (*Lolium temulentum* (L.) Darnel). In addition, monoculture wheat received 0.004 μL a.i. m^{-2} of triasulfuron preplant during 1992 and 1993 to control the increasing pressure of ryegrass. Diomethoate at 0.06 μL m^{-2} was sprayed one to two times per year in January to February to control green bug (*Schizaphis graminum* Rondani). Propiconazole at 0.03 mL m^{-2} was sprayed once to twice per year in March to April to control rust (*Puccinia* spp.) and powdery mildew (*Erysiphe* spp.).

Herbicide application in soybean consisted of 0.2 μL m^{-2} of glyphosate once to twice per year during February to May in NT, 0.4 μL m^{-2} of alachlor at planting, and either a sathoxydim/acifluorfen mixture or bentazon once to twice as a postemergent spray during July to September. Methyl parathion at 0.1 g a.i. m^{-2} was sprayed postemergent once to twice per year for control of three-cornered alfalfa hopper (*Spissistilus festinus* Say) and two to three times per year for control of stinkbug (Pentatomidae family).

Crop management variables were arranged as a split, split plot design with crop sequence as the main plot, tillage as the split plot, and N fertilizer rate as the split, split plot. Split, split plots measured 4 m $\times$ 12.2 m. Treatments were replicated four times.

Crop yield and N concentration

Sorghum grain was harvested by hand from a 6.6 m^2 area from 1983 to 1991 and by machine from a 24 m^2 area from 1992 to 1993. Grain from wheat and soybean was harvested and threshed by machine from a 24 m^2 area from 1983 to 1993. Grain yield was adjusted to 14% moisture. Sorghum stover was cut at ground level from a 6.6 m^2 area in 1991 and 1992 and from a 3.3 m^2 area in 1993 after grain harvest. Stover was weighed in the field on a portable scale, three stalks were air-dried followed by oven-drying at 60°C for 2 days for moisture determination, and the remainder returned to the original plot. Wheat plants were cut by hand at ground level prior to machine harvest from a 0.8 m^2 area in 1992 and 1993. Whole plant samples were air-dried followed by oven-drying at 60°C for 2 days before weighing. Wheat grain was threshed, weighed, and the difference between whole-plant and grain samples represented the stover weight. Soybean plants were cut by hand at ground level from a 2.0 m^2 area during early leaf drop in 1991 and 1992. Recently deposited leaf litter was also collected. Whole plant samples were divided into litter, stems, leaves, and pods plus grain. Components were air-dried followed by oven-drying at 60°C for 2 days before weighing. Soybean grain was threshed from pods, weighed, and the difference from the pod plus grain represented pod weight. The hand-cut wheat and soybean residues were not returned to the field.

Grain subsamples of sorghum and wheat were ground to <1 mm, digested in $H_2SO_4/H_2O_2/LiSO_4$ (Nelson and Sommers, 1980), and the NH_4-N concentration of diluted digests determined with autoanalyzer techniques (Technicon Industrial Systems, 1977). Stover subsamples of all crops and soybean grain were ground to < 1 mm, digested in H_2SO_4 (Gallaher et al., 1976), and the NH_4-N concentration of diluted digests determined with autoanalyzer techniques.

Statistical analyses

Linear relationships between hand-harvested stover and grain yields during 1991 to 1993 for sorghum, 1992 to 1993 for wheat, and 1991 to 1992 for soybean were used to predict stover yields for all years of this study.

Grain and stover yields were analyzed for differences among tillage, crop sequence, and N fertilizer variables with the general linear model (GLM) procedure of SAS (SAS Institute Inc., 1985) using yearly means from 1984 to 1993. Yield in 1983 was not included because the rotation sequences were not fully developed. The sorghum-wheat/soybean sequence was analyzed for each year of the 2-yr rotation separately, as well as for the complete rotation by averaging the two years. Yearly variation was either separated as a blocking effect or used as a covariate to test for temporal changes with tillage, crop sequence, and N fertilizer rate as sources of variation arranged in a factorial manner for each crop. Grain yield response to N fertilizer was described by a second-order polynomial equation for each of the tillage $\times$ crop sequence combinations. Optimal yield was calculated as 95% of maximum yield from individual regression equations. We assumed that economically optimum yield would be approximately 95 to 98% of maximum to achieve maximum economic yield and that environmentally optimum yield was approximately 90 to 95% of maximum to reduce the likelihood of excessive nitrate accumulation, which might impact groundwater quality.

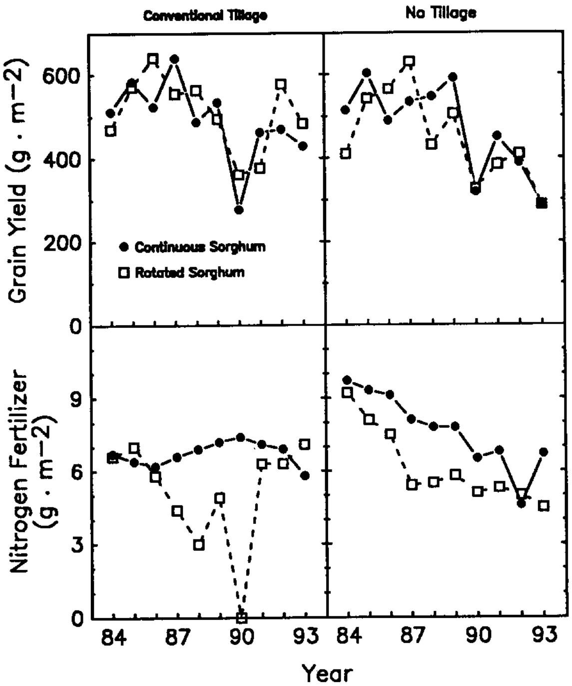

Fig. 1. Optimum sorghum grain yield (i.e. 95% of maximum) and N fertilizer requirement as affected by tillage and crop sequence during 1984 to 1993.

Differences in N concentration of grain and stover among tillage, crop sequence, and N fertilizer variables were analyzed with the GLM procedure using the 2 to 3 years of data available.

Results and discussion

Grain yield

Sorghum grain yield at 95% of maximum yield, considered an optimal yield based on fluctuating grain and N fertilizer prices and environmental considerations, varied from 280 to 640 g m^{-2} (Fig. 1). Yearly variation was partially due to differences in rainfall distribution among years (Table 1), but was also due to cultural variation (i.e. hybrid selection, pest control effectiveness, stand establishment, etc.). Averaged across the 10 years, crop sequence had no effect on sorghum grain yield. In addition, there was no obvious difference between crop sequences with time. Thus, continuous culture had no adverse effect on sorghum grain production, at least during the first 10 years. In Indiana, corn rotated with soybean was similar in yield compared to monoculture early in the study, but increased 10 to 24 g m^{-2} yr^{-1} more than in monoculture with time, depending upon tillage regime (Griffith et al., 1988).

Optimal sorghum grain yield averaged across years and crop sequences was greater with CT (501 g m^{-2}) than with NT (461 g m^{-2}). This occurred even though sorghum with CT required 14% less N fertilizer to reach optimal yield than with NT (Fig. 1). Optimal sorghum grain yield required an average of 6.7 and 5.1 g N fertilizer m^{-2} with CT in monoculture and in rotation, respectively, and 7.6 and 6.1 g N fertilizer m^{-2} with NT. Soil organic matter content at a depth of 0 to 200 mm depth with CT was reduced by an average of 6% compared with that of NT after nine years in sorghum management systems (Franzluebbers et al., 1994c) and by an average of 21% in wheat management systems (Franzluebbers et al., 1994b). Greater sequestration of N into SOM under NT probably led to a greater reliance of sorghum yield on fertilizer N compared to CT. At this same location, Locke and Hons (1988) reported that sorghum under NT took up 1.6 g m^{-2} more ^{15}N-labelled fertilizer than under CT, despite production of equivalent grain yield.

Under both tillage regimes, optimal sorghum grain yield in monoculture required more N fertilizer than in rotation (Fig. 1). This is in agreement with other studies comparing monoculture cereal grain production with various rotations (Baldock and Musgrave, 1980; Franzluebbers et al., 1994a; Roder et al., 1989). This effect is often attributed to decomposition of legume residues with higher N concentration than most cereal residues. In a companion study (unpubl. data), we measured higher soil microbial biomass and mineralizable C and N in rotated sorghum compared to monoculture sorghum in fertilized and unfertilized soil under both CT and NT. Larger pools of more biologically active soil C and N in rotation may have contributed to these differences in N fertilizer requirement.

Interesting trends of converging N requirement between tillage regimes with time and diverging N requirement between crop sequences with time were observed, although not significant at $p \leq 0.1$ (Fig. 2). These trends indicate that upon initiation of NT, attainment of optimal sorghum grain yield required 45% more N fertilizer than monoculture sorghum with CT and 67% more N fertilizer than rotated sorghum with CT. However, after 11 years of continual NT, the N fertilizer requirement became similar to that with CT. This was probably a result of initial immobilization of soil N into SOM by surface-placed crop residues with NT

Table 1. Mean air temperature (1951–1980) and yearly precipitation from 1983 to 1993 (National Oceanic and Atmospheric Administration, 1983–1993)

Month	Mean (°C)	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
							(mm)					
Jan	10	102	40	53	30	18	14	162	74	396	125	152
Feb	12	79	24	86	47	106	29	27	99	NA	249	50
Mar	16	141	88	40	9	50	74	90	77	58	92	117
Apr	20	12	2	72	46	16	35	25	167	NA	95	98
May	24	289	115	96	234	195	43	102	58	89	158	184
Jun	27	60	131	33	135	247	38	106	43	140	132	282
Jul	29	60	10	98	5	33	63	74	85	25	22	0
Aug	29	127	71	15	126	23	8	72	54	67	12	2
Sep	26	186	13	130	103	96	19	18	145	172	21	52
Oct	21	51	327	167	103	9	28	51	64	73	91	126
Nov	15	73	61	132	74	85	33	44	65	32	122	77
Dec	11	41	93	45	125	103	67	25	49	190	112	61
Sum		1221	975	967	1037	981	451	796	980	>1242	1231	1201

NA = not available.

Table 2. Coefficients of variation of mean yearly grain yield as affected by tillage, crop sequence and N fertilization during 1984 to 1993

N Fertilizer rate	Sorghum[a]	Sorghum-Wheat/Soybean	Wheat	Soybean	Wheat/Soy	Sorghum-Wheat/Soy	Sorghum-Wheat/Soy[b]
				(%)			
Conventional tillage							
0	34	21	44	58	45	41	24
L	22	17	43	NA	40	36	21
M	20	20	40	NA	41	36	23
H	22	17	42	NA	43	38	22
No tillage							
0	41	27	60	74	54	46	32
L	19	26	53	NA	45	40	27
M	21	23	53	NA	38	35	25
H	32	29	49	NA	43	41	32

[a]Underline represents the crop under consideration.
[b]The sorghum-wheat/soybean sequence represents the average of the sorghum and wheat/soybean phases of the rotation.
NA = not applicable.

and greater turnover of soil and crop residue N with CT. This initial period was then followed by greater release of N with NT due to increased SOM content (Franzluebbers et al., 1994b). In a long-term study in Kentucky, Ismail et al. (1994) reported reduced yield of corn receiving no N fertilizer with NT compared to CT early in the study, but greater yield with NT than with CT later in the study. Between crop sequences, the temporal divergence in N fertilizer requirement may have been due to the increasing benefit of fixed N with soybean in the rotation and/or other yield enhancing benefits of crop rotation with time. Little direct information exists in the literature for comparison of this effect.

Optimal grain yield (i.e. 95% of maximum yield) in monoculture wheat, monoculture soybean, continuous

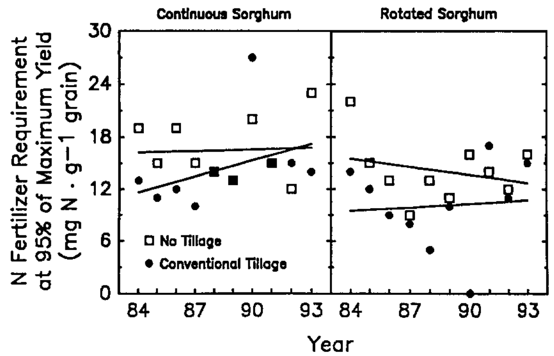

Fig. 2. Temporal trend in N fertilizer requirement per unit of optimum sorghum grain produced (i.e. 95% of maximum) as affected by crop sequence and tillage.

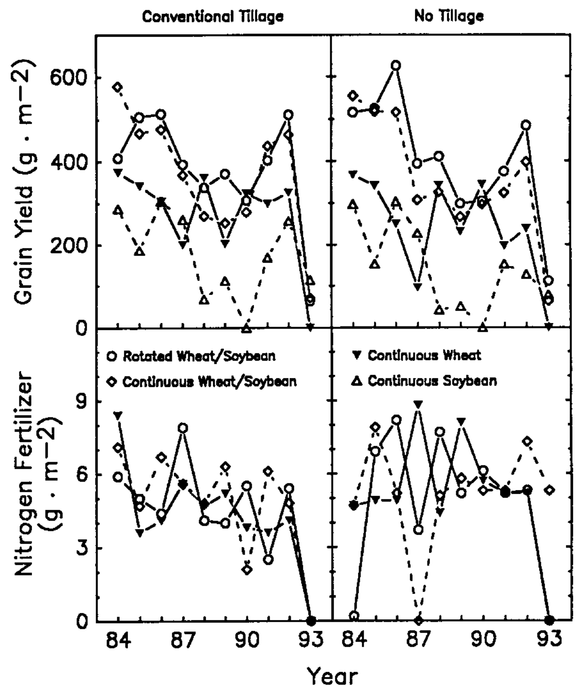

Fig. 3. Optimum wheat and soybean yield (i.e. 95% of maximum) and N fertilizer requirement as affected by tillage and crop sequence during 1984 to 1993.

wheat/soybean, and rotated wheat/soybean was not different between tillage regimes when averaged across years (Fig. 3). Optimal grain yield averaged 176 g m^{-2} for monoculture soybean, 257 g m^{-2} for monoculture wheat, 362 g m^{-2} for continuous wheat/soybean, and 393 g m^{-2} for rotated wheat/soybean. Wheat/soybean sequences yielded 80 to 170 g m^{-2} more grain at different N fertilizer levels than monoculture wheat because of the combined yield of wheat and soybean. Sorghum

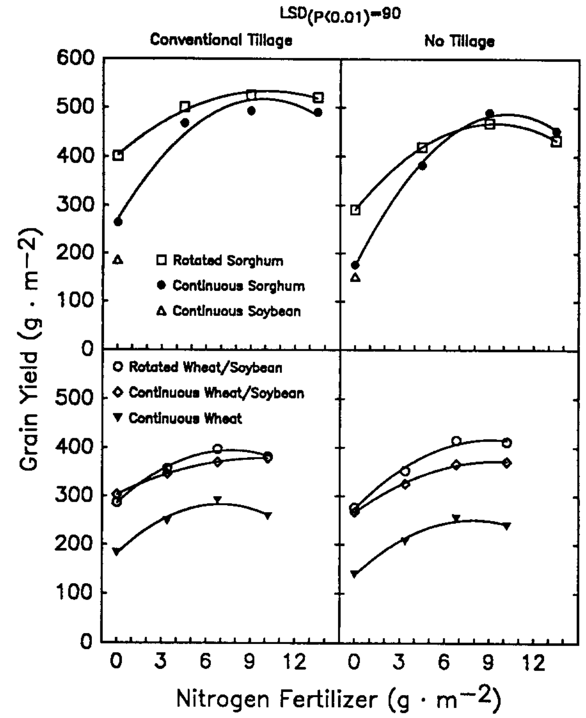

Fig. 4. Mean grain yield response to N fertilizer as affected by tillage, crop and crop sequence.

grain yield was greater than all other crops, averaging 461 g m^{-2} under NT and 501 g m^{-2} under CT.

Grain yield response to N fertilizer averaged across all years was greatest in continuous sorghum (Fig. 4). Sorghum yielded an average of 125 g m^{-2} more grain in rotation than in monoculture without N fertilization. The shape of grain yield response curves to N fertilizer was similar among wheat and wheat/soybean crop sequences. Wheat yield receiving 6.8 g N fertilizer m^{-2} averaged 71% of monoculture wheat in continuous wheat/soybean and 80% of monoculture wheat in rotated wheat/soybean under CT and 83% and 95%, respectively, under NT. Soybean yield in wheat/soybean sequences averaged 85 to 120% of that in monoculture soybean. However, since wheat/soybean sequences produced two crops per year, mean optimal grain yield was 63 and 86% greater in continuous wheat/soybean and 70 and 111% greater in rotated wheat/soybean than the combined yield of monoculture wheat and monoculture soybean on an equivalent land area basis under CT and NT, respectively.

Land use was intensified with double cropping. Resource input via N fertilizer, however, decreased per unit of grain produced. Continuous wheat/soybean

Table 3. Mean yearly estimated crop residue production[a] as affected by tillage, crop sequence, and N fertilization during 1984 to 1993. The least significant difference [$LSD_{(p \leq 0.1)}$] between means of crop sequence and tillage combinations are 120, 110, 111, and 131 g m^{-2} for N fertilizer rates of 0, L, M, and H, respectively

N Fertilizer rate[b]	Sorghum[c]	Sorghum-Wheat/Soy	Wheat	Soybean	Wheat/Soy	Sorghum-Wheat/Soy	Sorghum-Wheat/Soy[d]
				(g m^{-2})			
Conventional tillage							
0	400	456	360	543	754	727	592
L	483	497	498	NA	840	875	686
M	494	507	587	NA	912	965	740
H	492	505	523	NA	934	947	739
No tillage							
0	364	411	276	440	670	719	565
L	448	463	420	NA	800	882	673
M	492	483	523	NA	903	1009	748
H	477	469	535	NA	918	1001	735

[a] Crop residue production estimated from stover to grain ratios during 1991–1993.
[b] 0 = no N fertilizer, L = low rate (4.5 g m^{-2} in sorghum and 3.4 g m^{-2} in wheat), M = medium rate (9.0 g m^{-2} in sorghum and 6.8 g m^{-2} in wheat), and H = high rate (13.5 g m^{-2} in sorghum and 10.2 g m^{-2} in wheat).
[c] Underline represents the crop under consideration.
[d] The sorghum – wheat/soybean sequence represents the average of the sorghum and wheat/soybean phases of the rotation.

Table 4. Mean N concentration of sorghum (1991–1993) and wheat (1992–1993) stover as affected by tillage, crop sequence,and N fertilization

Crop	Tillage[b]	Crop sequence	Nitrogen fertilizer level (mg g^{-1})[a] None	Low	Medium	High	$LSD_{(p<0.01)}$[c]
Sorghum	CT	Monoculture	4.8	5.8	6.6	9.9	
		Sorghum-Wheat/Soybean	5.7	6.6	8.6	9.3	
							1.7
	NT	Monoculture	4.0	4.9	5.7	7.6	
		Sorghum-Wheat/Soybean	5.3	6.5	7.5	8.5	
Wheat	CT	Monoculture	4.1	4.5	6.0	9.1	
		Wheat/Soybean	4.3	5.0	5.8	7.3	
		Sorghum-Wheat/Soybean	4.8	4.7	6.3	6.9	
							1.2
	NT	Monoculture	4.9	5.0	6.4	7.6	
		Wheat/Soybean	5.8	5.5	6.5	7.8	
		Sorghum-Wheat/Soybean	4.4	4.6	6.0	7.7	

[a] None = no N fertilizer,Low = 4.5 g m^{-2} in sorghum and 3.4 g m^{-2} in wheat, Medium = 9.0 g m^{-2} in sorghum and 6.8 g m^{-2} in wheat, and High = 13.5 g m^{-2} in sorghum and 10.2 g m^{-2}in wheat.
[b] CT = conventional tillage and NT = no tillage.
[c] Least significant difference (LSD) is between means of N fertilizer, crop sequence,and tillage combinations within a crop.

Table 5. Mean N concentration of soybean components (1991–1992) as affected by tillage and crop sequence

Tillage[a]	Crop sequence	Component ($mg\ g^{-1}$) Grain	Pods	Leaves	Stems	Litter	Stover mean ($mg\ g^{-1}$)
CT	Monoculture	64.2	12.1	16.1	7.9	11.3	12.3
	Wheat/Soybean	64.1	12.3	20.3	8.5	12.5	14.5
	Sorghum-Wheat/Soybean	63.6	12.4	20.7	7.6	12.7	14.7
NT	Monoculture	63.1	11.5	17.4	8.1	15.1	13.5
	Wheat/Soybean	63.4	12.4	23.1	9.9	18.5	16.5
	Sorghum-Wheat/Soybean	63.0	13.8	24.4	10.8	19.0	17.7
$LSD_{(p<0.01)}$[b]		2.6	2.0	4.2	1.8	1.8	2.2

[a] CT = conventional tillage and NT = no tillage.
[b] Least significant difference (LSD) is between means of crop sequence and tillage combinations within a plant component.

required an average of 13 and 21 g N kg^{-1} grain, while rotated sorghum-wheat/soybean required only 11 and 13 g N kg^{-1} grain under CT and NT, respectively. However, monoculture sorghum required 15 and 17 g N kg^{-1} grain and monoculture wheat required 15 and 25 g N kg^{-1} grain under CT and NT, respectively. Efficiency of land use for grain production in southcentral Texas could, therefore, be increased with more intensive cropping sequences receiving moderate N fertilization.

Yearly variation in grain yield was least for sorghum and greatest for soybean (Table 2). Crop failure did not occur with sorghum, but occurred in all soybean sequences due to drought during 1990 and in all wheat sequences due to bird damage during 1993. Soybean was grown during the most stressful period in southcentral Texas when rainfall was scarce and evaporative demand was high (Table 1). These crop failures, in part, contributed to the higher variability in grain yield with wheat and soybean crops compared to sorghum. The coefficients of variation were also higher in soybean and wheat due to lower grain yield than in sorghum. Reliability of grain yield, therefore, was greatest in rotated sorghum-wheat/soybean and in monoculture sorghum. Nitrogen fertilization to achieve optimum yield tended to lower the year-to-year variation in all crop sequences. Similar results were reported for corn in central Texas (Mjelde et al., 1991). Averaged across N fertilizer rates, yearly variation in yield was lower with CT than with NT. This result may have been due to greater variability in stand establishment with NT than with CT.

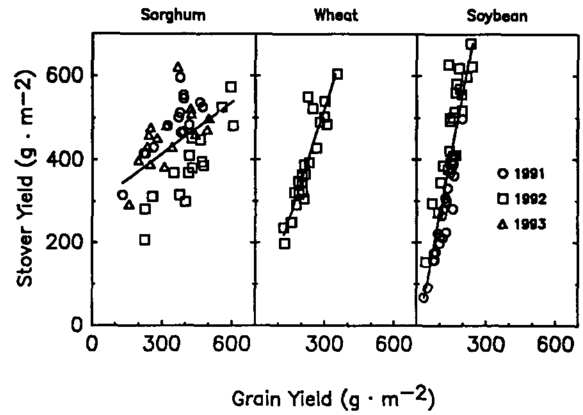

Fig. 5. Relationship between stover and grain production for sorghum (Stover = 291 + 0.41 × grain, $R^2 = 0.271$, 1991 to 1993), wheat (Stover = 2 + 1.73 × grain, $R^2 = 0.836$, 1992), and soybean (Stover = -29 + 2.94 × grain, $R^2 = 0.787$, 1991 to 1992).

Crop residue production

Although sorghum produced more grain than wheat and soybean, the ratio of stover to grain was greater in wheat and soybean (Fig. 5). Therefore, wheat and soybean produced as much crop residue as sorghum (Table 3), suggesting that all crops potentially had a high degree of cycling of organically-bound nutrients in the form of crop residues back to the soil system. The intercept of the relationship between stover and grain production was significantly different from zero only in sorghum. This relationship implies that sorghum may be able to respond better to fluctuating moisture conditions by producing abundant dry matter during all conditions, followed by a liberal period of grain pro-

Table 6. Mean yearly grain N removal[a] and stover N return as affected by tillage, crop sequence, and N fertilization

Crop sequence[b]	Nitrogen fertilizer[c]	Grain (g N m^{-2}) CT[d]	Grain (g N m^{-2}) NT	Stover (g N m^{-2}) CT	Stover (g N m^{-2}) NT
Sorghum[d]	O	2.4	2.0	1.7	1.1
	L	5.3	3.9	2.6	1.8
	M	6.7	5.3	3.2	2.4
	H	6.9	4.6	5.1	3.0
Sorghum-	O	4.4	3.3	2.5	2.1
Wheat/Soybean	L	6.3	4.6	3.6	2.9
	M	7.4	6.0	4.4	3.4
	H	7.9	5.5	4.7	3.9
Wheat	O	3.8	3.1	1.6	1.5
	L	5.8	3.6	2.7	2.3
	M	7.8	5.2	4.3	4.4
	H	7.2	5.1	5.9	6.8
Soybean	O	11.2	8.4	6.3	5.1
Wheat/Soybean	O	13.6	8.8	7.7	6.0
	L	14.4	9.9	8.5	6.9
	M	16.0	10.8	9.6	8.1
	H	15.0	11.7	10.8	9.3
Sorghum-	O	11.4	9.9	6.4	6.8
Wheat/Soybean	L	13.3	11.5	7.1	7.8
	M	13.2	14.4	8.7	9.7
	H	16.2	14.4	9.6	11.0
Sorghum-	O	7.9	6.6	4.5	4.5
Wheat/Soybean[e]	L	9.8	8.1	5.4	5.3
	M	10.3	10.2	6.6	6.6
	H	12.0	10.0	7.2	7.5
$LSD_{(p<0.01)}$[f]		1.6		1.2	

[a] Average of 1991–1993 for sorghum, 1992–1993 for wheat, and 1991–1992 for soybean.
[b] Underline represents the crop under consideration.
[c] 0 = no N fertilizer, L = low rate (4.5 g m^{-2} in sorghum and 3.4 g m^{-2} in wheat), M = medium rate (9.0 g m^{-2} = in sorghum and 6.8 g m^{-2} in wheat), and H = high rate (13.5 g m^{-1} in sorghum and 10.2 g m^{-2} in wheat).
[d] CT = conventional tillage and NT = no tillage.
[e] The sorghum-wheat/soybean sequence represents the average of the sorghum and wheat/soybean phases of the rotation.
[f] Least significant difference (LSD) is between means of N fertilizer, crop sequence, and tillage combinations within a plant component (i.e. grain or stover).

duction whenever sufficient moisture becomes available (Quisenberry, 1982). Grain:stover ratios would be low under water and nutrient stress and high under optimal water and nutrient conditions.

Rotation sequences produced up to nearly double the quantity of crop residues than did monoculture sequences because of more intensive cropping (Table 3). Sorghum residue production was greater than wheat residue production without N fertilization, but less than wheat residue production at medium and high N fertilizer levels. Soybean residue production without N fertilizer was comparable to sorghum and wheat residue production at optimal N fertilizer levels. Greater than or equal crop residue production of all crops occurred with CT compared to NT.

Crop residue N concentration was affected primarily by crop, but also by N fertilization (Tables 4 and 5). The quality of stover was greatest in soybean with average N concentration ranging from 12 to 18 mg N g^{-1}, and only 4 to 10 mg N g^{-1} for sorghum and wheat stover. Large differences in N concentration occurred among soybean plant components. Soybean grain averaged 64 mg N g^{-1}, leaves averaged 20 mg N g^{-1}, recently-deposited litter averaged 15 mg N g^{-1}, pods averaged 12 mg N g^{-1}, and stems averaged 9 mg N g^{-1}.

Sorghum and wheat stover N concentration increased with N fertilization (Table 4). Sorghum residue N concentration averaged 5, 6, 7, and 9 mg N g^{-1} with 0, 4.5, 9.0, and 13.5 g N m^{-2}, respectively. Sorghum residue N concentration in rotation tended to be greater than in monoculture at low N fertilizer levels. Wheat residue N concentration averaged 5, 5, 6, and 8 mg N g^{-1} with 0, 3.4, 6.8, and 10.2 g N fertilizer m^{-2}, respectively.

Increased grain production in rotation sequences compared to monoculture sequences without the need for more N fertilizer may have been partly a result of greater return of crop residue N (Table 6). At the high N fertilizer level, for example, monoculture sorghum returned 5 and 3 g N m^{-2} in the form of crop residues with CT and NT, respectively, but 7 g N m^{-2} with both tillage regimes in the sorghum-wheat/soybean sequence. Increased crop residue input led to a greater reservoir of SOM, especially with NT (Franzluebbers et al., 1994b). Bauer and Black (1994) also demonstrated that maintenance of high levels of SOM led to more sustained production. The larger, more diverse, and more frequent input of crop residues in rotation supplied soil microorganisms with a more continual supply of C substrates that led to greater mineralization/immobilization turnover of N (Jansson and Persson, 1982). A larger pool of more active soil C and N probably led to a more continual supply of mineralized N that was available for crop uptake. Soil with more mineralization/immobilization turnover would also probably present less opportunities for loss of N through leaching and denitrification, because only moderate levels of inorganic N would be present.

References

Baldock J O and Musgrave R B 1980 Manure and mineral fertilizer effects in continuous and rotational crop sequences in central New York. Agron. J. 72, 511–518.

Barber S A 1972 Relation of weather to the influence of hay crops on subsequent corn yields on a Chalmers silt loam. Agron. J. 64, 8–10.

Bauer A and Black A L 1994 Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58, 185–193.

Cook R J 1984 Root health: Importance and relationship to farming practices. *In* Organic Farming: Current Technology and Its Role in a Sustainable Agriculture. Eds. D F Bezdicek and J F Powers. pp 111–127. Am. Soc. Agron. Special Publ. 46. Am. Soc. Agron., Madison, WI.

Copeland P J and Crookston R K 1 992 Crop sequence affects nutrient composition of corn and soybean grown under high fertility. Agron. J. 84, 503–509.

Crookston R K, Kurle J E, Copeland P J, Ford J H and Lueschen W E 1991 Rotational cropping sequence affects yield of corn and soybean. Agron. J. 83, 108–113.

Dick W A and Van Doren D M Jr 1985 Continuous tillage and rotation combinations effects on corn, soybean and oat yields. Agron. J. 77, 459–465.

Fahad A A, Mielke L N, Flowerday A D and Swartzendruber D 1982 Soil physical properties as affected by soybean and other cropping sequences. Soil Sci. Soc. Am. J. 46, 377–381.

Franzluebbers A J, Francis C A and Walters D T 1994a Nitrogen fertilizer response potential of corn and sorghum in continuous and rotated crop sequences. J. Prod. Agric. 7, 277–284.

Franzluebbers A J, Hons F M and Zuberer D A 1994b Long-term changes in soil carbon and nitrogen pools in wheat management systems. Soil Sci. Soc. Am. J. 58, 1639–1645.

Franzluebbers A J, Hons F M and Zuberer D A 1994c Soil organic carbon, microbial biomass and mineralizable carbon and nitrogen in sorghum management systems. Soil Sci. Soc. Am. J. (*In press*).

Gallaher R N, Weldon C O and Boswell F C 1976 A semiautomated procedure for total nitrogen in plant and soil samples. Soil Sci. Soc. Am. J. 40, 887–889.

Griffith D R, Kladivko E J, Mannering J V, West T D and Parsons S D 1988 Long-term tillage and rotation effects on corn growth and yield on high and low organic matter, poorly drained soils. Agron. J. 80, 599–605.

Ismail I, Blevins R L and Frye W W 1994 Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci. Soc. Am. J. 58, 193–198.

Jansson S L and Persson J 1982 Mineralization and immobilization of soil nitrogen. *In* Nitrogen in Agricultural Soils. Ed. F J Stevenson. pp 229–252. Monogr. 22, Am. Soc. Agron., Madison, WI.

Jawson M D, Franzluebbers A J, Galusha D K and Aiken R M 1993 Soil fumigation within monoculture and rotations: Response of corn and mycorrhizae. Agron. J. 85, 1174–1180.

Locke M A and Hons F M 1988 Tillage effect on seasonal accumulation of labeled fertilizer nitrogen in sorghum. Crop Sci. 28, 694–700.

Mjelde J W, Cothren J T, Rister M E, Hons F M, Coffman C G, Shumway C R and Lemon R G 1991 Integrating data from various field experiments: The case of corn in Texas. J. Prod. Agric. 4, 139–147.

National Oceanic and Atmospheric Administration 1983-1993 Climatological data, Texas. National Oceanic and Atmospheric Administration, United States Department of Commerce.

Nelson D W and Sommers L E 1980 Total nitrogen analysis for soil and plant tissues. J. Assoc. Off. Anal. Chem. 63, 770–778.

Power J F 1990 Legumes and crop rotations. *In* Sustainable Agriculture in Temperate Zones. Eds. C A Francis, C B Flora and L D King. pp 178–204. John Wiley and Sons, New York.

Quisenberry J E 1982 Breeding for drought resistance and plant water use efficiency. *In* Breeding Plants for Less Favorable Environments. Eds. M N Christiansen and C F Lewis. pp 193–212. John Wiley and Sons, New York.

Roder W, Mason S C, Clegg M D and Kniep K R 1989 Crop root distribution as influenced by grain sorghum-soybean rotation and fertilization. Soil Sci. Soc. Am. J. 53, 1464–1470.

SAS Institute Inc 1985 SAS USer's Guide: Statistics version. 5th ed. SAS Institute, Cary, NC.

Technicon Industrial Systems 1977 Determination of nitrogen in BS digests. Technicon industrial method 334–74 W/B. Technicon Industrial Systems, Tarrytown, NY.

Turco R F, Bischoff M, Breakwell D P and Griffith D R 1990 Contribution of soil-borne bacteria to the rotation effect in corn. Plant and Soil 122, 115–120.

Whiting K R and Crookston R K 1993 Host-specific pathogens do not account for the corn-soybean rotation effect. Crop Sci. 33, 539–543.

Section editor: H Marschner