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INFLUENCE OF CORN (*ZEA MAYS* L.) CULTIVAR DEVELOPMENT ON RESIDUE PRODUCTION

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□ *The amount and composition of crop residues added to soil in agroecosystems can influence decomposition processes and soil organic matter levels. This study aimed to evaluate residues (quantity and quality) of different corn cultivars commonly used in Brazilian cropping systems. The experiment was conducted for two seasons (2005/2006 and 2006/2007) in Rolândia, Paraná State, Brazil. Ten corn cultivars that represent five degrees of breeding development (i.e., landrace, commercial variety, double cross, triple cross, and single cross hybrids) were evaluated. At harvest, carbon (C) and nitrogen (N) of non-yield residue and grain were determined. Except for grain C, other measures (grain N concentration, residue C and N concentration, and C:N ratio) varied among cultivars. In general, the hybrids had higher residue C and lower residue N concentrations than the landraces and commercial varieties. Findings suggest that breeding selection may have altered residue production and composition, which may influence soil C dynamics.*

Keywords: *Zea mays* L., corn cultivars, C and N concentration, residue quality

INTRODUCTION

Soil organic matter is known to have tremendous potential to increase sustainability and productivity by improving soil fertility, nutrient use efficiency, and overall soil quality (Delgado and Follett, 2002; Lal, 2009). Differential changes in the quantity and quality of plant tissue entering the

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soil system may affect residue residence time, nutrient turnover, and soil physical properties (Prior et al., 2004). An important conservation agriculture principle is the retention of adequate crop residues on the soil surface for protection from water/wind erosion, water run-off/evaporation, and improvement in soil physicochemical and biological properties needed for long-term sustainability (Govaerts et al., 2009).

Recent efforts have focused on increasing soil organic matter by adopting cropping systems that use reduced- or no-tillage practices (Amado et al., 2001; Lal, 2004; Sisti et al., 2004; Diekow et al., 2005; Bayer et al., 2006). The adoption of no-tillage alone may not sufficiently increase soil organic matter, but crop intensification may result in more carbon (C) storage in these systems (Govaerts et al., 2009). West and Post (2002) reported that C increases due to adoption of no-tillage were greater and occurred much faster in continuously-cropped systems, while C increases were much smaller in fallow-based rotations. Soil organic matter can be enhanced by increasing C inputs through addition of foreign residues (e.g., compost and animal manure), using higher residue-producing crops, or adopting systems using crop rotations and cover crops (Havlin et al., 1990; Pretty and Ball, 2001; Lal, 2009).

Grass crops have been shown to enhance crop residue quantity and soil C sequestration (Six et al., 2001; Lovato et al., 2004; Yang et al., 2004; Salton, 2005). Among grasses, corn (*Zea mays* L.) is a major crop in many developed countries and has been used in crop rotations to maintain or increase soil organic C. However, developing countries use a wide diversity of corn varieties (from landraces to single-cross hybrids) that exhibit large differences in production potential. Nevertheless, the amount of C and quality of residue from different corn varieties are largely unknown.

Carbon uptake in crops occurs through photosynthesis and this C enters the soil as biomass residue. This input and any changes to plant tissue chemistry can influence soil C cycling and sequestration in agroecosystems (Martens, 2000). Decomposition studies have found that increased soil C turnover may correspond weakly with soil C, suggesting that residue quality influences C cycling (Torbert et al., 2000). Prior et al. (2006) observed soybean varietal differences in residue C and N and concluded that the breeding selection process may have altered residue quality that impacted soil C or nitrogen (N) mineralization. Further studies are needed to identify differences in residue quality among crop varieties to enhance our abilities to predict how these differences might impact soil C and N cycling in agricultural systems. In the present study, we evaluated biomass (grain and non-yield residue) C and N of ten corn cultivars (representing five technology levels of the breeding selection process) that are used in Brazilian no-tillage cropping systems.

MATERIALS AND METHODS

Experimental Details

Field experiments were conducted during the 2005/2006 and 2006/2007 growing seasons at the Monsanto Company Experimental Station in Rolândia County (23°16′ S, 51°28′ W, 645 m altitude), Paraná State, southern Brazil. The soil is classified as a Rhodic Ferralsol Eutric (FAO, 2006). The climate is classified as Cfa according to the Köppen Climate Classification System. This classification uses regionalization of world climates based on the annual cycle of climatic elements (mainly air temperature and monthly precipitation) and their effects on vegetation (Martyn, 1992; Pereira et al., 2002). The Cfa index means warm temperate climate with regular precipitation throughout the year (subtropical or mesothermic), without a dry season. The colder average monthly temperature is between −3°C and 18°C and the hotter average monthly temperature is below 22°C; winter frosts are uncommon and summers are hot with rainfall tending to be concentrated during summer months.

Five pairs of corn cultivars representing different degrees of breeding development were selected (Table 1). The pairs were: (1) landraces

TABLE 1 Characteristics of ten corn cultivars evaluated during both growing seasons

Cultivar	General characteristics
AG9010	Single cross hybrid; very early maturity; 770 GDU†; upright leaves; high investment level‡; released 1998
DKB950	Single cross hybrid; very early maturity; 770 GDU; semi-erect leaves; high investment level; released 2000
AG5020	Triple cross hybrid; early maturity; 865 GDU; semi-erect leaves; medium/high investment level; released 2003
DKB566	Triple cross hybrid; early maturity; 840 GDU; semi-erect leaves; medium/high investment level; released 2003
AG2040	Double cross hybrid; early maturity; 875 GDU; semi-erect leaves; medium investment level; released 2003
DKB979	Double cross hybrid; early maturity; 855 GDU; semi-erect leaves; medium investment level; released 2003
BRS4157	Commercial variety; early maturity; 751 GDU; low/medium investment level; released 1999
BR106	Commercial variety; intermediate maturity; 788 GDU; low/medium investment level; released 1998
GI045§	Landrace; intermediate maturity; low investment level; originated from the border between Paraguay and Paraná State in southern Brazil
Palotina	Landrace; late maturity; low investment level; originated from the west of Paraná State in southern Brazil

†Growing degree unit.

‡Investment level is related to seed cost and management system for optimal growth (i.e., high investment level implies more expensive seeds, agricultural inputs, and cultural practices).

§Identification by Instituto Agronômico do Paraná (IAPAR); Tupy Pyta Sopé is the common name.

[*Palotina* and *Tupy Pyta Sopé* (GI045)]; (2) commercial varieties ('BR106' and 'BRS4157'); (3) double cross hybrids ('AG2040' and 'DKB979'); (4) triple cross hybrids ('AG5020' and 'DKB566'); and (5) single cross hybrids ('AG9010' and 'DKB950). These cultivar pairs were intended to represent available corn seed used in Brazilian cropping systems. Over the last 10 years, single cross hybrids represented 40% of all corn cultivars available for farmers compared to 28%, 21% and 11% for triple cross, double cross and commercial varieties, respectively (Cruz and Pereira Filho, 2008). There are no official statistics for landraces that represent a small fraction of the area used by subsistence farmers in Brazil. Weid (1998) defined landraces as varieties that have locally undergone a process of empirical breeding selection over generations; common landraces are phenotypically well-defined varieties that have been developed, adapted, and produced by indigenous and smallholder farmers.

In both years, cultivars were sown in a randomized complete block design with five replications, using six-row plots 10 m in length. Row width was 0.80 m, plant spacing within rows was 0.20 m, and established plant population was 62500 plants ha^{-1}. Fertilizer providing 28 kg N ha^{-1}, 70 kg phosphorus pentoxide (P_2O_5) ha^{-1} and 70 kg dipotassium oxide (K_2O) ha^{-1} was applied prior to sowing. Plots were hand-planted and thinned to the desired plant population at the V_2 stage (Ritchie et al., 1993). To minimize N restrictions, urea was supplied at 135 kg N ha^{-1} at the four-leaf stage (V_4). Plots were kept free of weeds, insects, and diseases following recommended practices for the region.

Growth Conditions

An on-site weather station recorded daily air temperature and rainfall throughout each season. Meteorological conditions differed between the two growing seasons (Figure 1). Historical total average rainfall during the rainiest quarter (December–February) in Rolândia County is between 500 and 600 mm (Caviglione et al., 2000). In this quarter of the 2005/2006 season, the study site received 503 mm of rain, while 796 mm was recorded in 2006/2007. Historical averages of total rainfall in December, January, and February are between 200–225 mm, 200–225 mm, and 150–175 mm, respectively (Caviglione et al., 2000). During the 2005/2006 season, total rainfall in December, January and February was 80, 56, and 367 mm, respectively. In the 2006/2007 season, the respective totals for these months were 226, 398, and 172 mm.

Plant Sampling and Measurement

At final harvest, fifteen whole plants were sampled from the second and fifth rows of each plot. Plants were separated into grain and residue

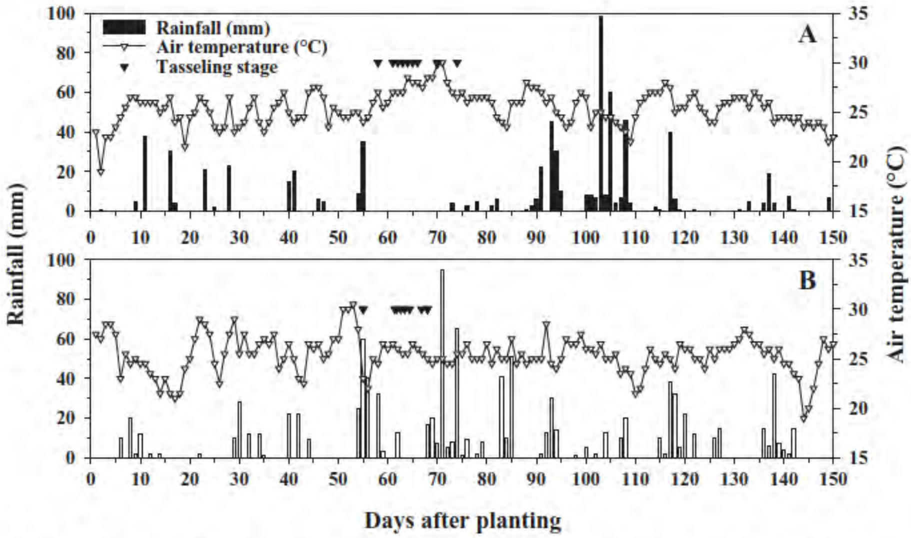

FIGURE 1 Daily rainfall and average air temperature after planting during the A) 2005/2006 and B) 2006/2007 growing seasons. Dark arrows indicate tasseling stage dates for the ten corn cultivars.

material that would normally remain in the field after harvest (i.e., stalk, leaves, cob, husks and tassel). The two middle rows of each plot were harvested for grain and grain moisture content was immediately determined using a M-3G portable moisture tester (DICKEY-John Corporation, Auburn, IL, USA). Residue material was oven dried (75°C) to constant weight prior to mass determinations. Total biomass (grain + residue) was calculated for each plot. The harvest index was the ratio of grain yield to total biomass.

Subsamples of residue and grain were ground in a Wiley mill to pass a 1.0 mm screen. Subsamples were analyzed in triplicate to determine the C and N concentration via the dry combustion method using a CN-2000 LECO Instrument (LECO Corporation, St. Joseph, MI, USA). The C and N content of grain and residue was calculated by multiplying corresponding dry weights by their respective C and N concentrations. The C harvest index was defined in this study as the ratio of total grain C content to total C biomass content (grain + residue).

Statistics

Data were analyzed as an ANOVA and for those variables with no significant year effect, the data were pooled over years by cultivar. As previously stated, the study was a randomized complete block design with five replications. Sources of variation were considered significant in all statistical calculations if P values ≤ 0.05. Mean separation between variables was obtained by Tukey's Least Significant Difference test. Pre-planned comparisons among cultivars were conducted using Student's *t* statistic and for this comparison some cultivar pairs were combined. These specific comparisons were: (i) single cross hybrids ('AG9010' and 'DKB950') vs. landraces ('GI045' and 'Palotina') and (ii) hybrids ('AG9010', 'DKB950', 'AG5020', 'DKB566', 'AG2040' and 'DKB979') vs. commercial varieties ('BRS4157' and 'BR106'). These comparisons aimed to evaluate contrasting groups of cultivars (in terms of corn breeding selection) to reproduce the technology evolution promoted by international breeding programs. This evolution in technology occurred in the following order: landraces, commercial varieties, double cross, triple cross, and single cross hybrids.

RESULTS

The critical water supply period for corn is from the tasseling stage to the beginning of grain filling (Bergamaschi et al., 2004) or fifteen days before and after the tasseling stage (Durães et al., 2004). The 2005/2006 season had a drought during this critical period where only 56 mm of rainfall occurred. In contrast, the 2006/2007 season had a more favorable rain distribution pattern and received 402 mm during this critical reproductive period (Figure 1).

In the first season (2005/2006), a drought during the tasseling stage (Figure 1) significantly affected grain yield (Table 2). The corn cultivar with the lowest yield was the landrace Palotina (192 kg ha^{-1}) and the highest was the triple cross hybrid 'DKB566' (2788 kg ha^{-1}). In contrast, the second growing season (2006/2007) had more uniformly distributed rainfall during tasseling, so this crop experienced less water stress relative to the first year's crop. During this season, Palotina (3987 kg ha^{-1}) remained the corn cultivar with the lowest yield and the triple cross hybrid 'AG5020' (8881 kg ha^{-1}) had the highest yield.

In general, drought had much smaller affect on non-yield residue production as shown in Table 2. However, the results indicated significant main effects of cultivar and year and their interaction. In the first growing season, the single cross hybrid 'DKB950' (6907 kg ha^{-1}) and landrace 'Palotina' (13469 kg ha^{-1}) had the lowest and highest residue production, respectively. In the second season, the cultivar with the lowest residue production was the single cross hybrid 'AG9010' (7414 kg ha^{-1}) and that with the highest was the double cross hybrid 'AG2040' (11227 kg ha^{-1}).

Total biomass (grain + residue) was affected by drought as the overall mean in the first season (12110 kg ha^{-1}) was smaller than the second season (16231 kg ha^{-1}) (Table 3). Total biomass varied from 8991 kg ha^{-1} ('DKB950') to 13661 kg ha^{-1} ('Palotina') in the dry year and from 13294 kg ha^{-1} ('GI045') to 19450 kg ha^{-1} ('AG2040') in the year with adequate rainfall distribution.

TABLE 2 Grain and residue dry matter production of ten corn cultivars for the 2005/2006 and 2006/2007 growing seasons

Cultivar		Grain†			Residue‡		
		2005/2006	2006/2007	Mean	2005/2006	2006/2007	Mean
					kg ha^{-1}		
Single	AG9010	1988ab§	8036ab	5012a	7807de	7414d	7610d
Single	DKB950	2084ab	7722ab	4903a	6907e	7669cd	7288d
Triple	AG5020	2442ab	8881a	5661a	11210bc	10478ab	10844ab
Triple	DKB566	2788a	7372bc	5080a	9494cd	9132abcd	9313c
Double	AG2040	1918ab	8223ab	5071a	10629bc	11227a	10928ab
Double	DKB979	2625a	8138ab	5382a	9199cd	9783abc	9491bc
Commercial	BRS4157	1747abc	4934d	3340b	10535bc	8821bcd	9678bc
Commercial	BR106	1451bc	6241c	3846b	11808ab	9904ab	10856ab
Landrace	GI045	611cd	4224d	2417c	12199ab	9070bcd	10635abc
Landrace	Palotina	192d	3987d	2090c	13469a	10346ab	11907a
	Mean	1785	6776		10326	9385	
				ANOVA			
Source of variation	df						
Cultivar (C)	9		<0.0001¶			<0.0001	
Year (Y)	1		<0.0001			<0.0001	
C × Y	9		<0.0001			<0.0001	
CV (%)			13.1			10.4	

†LSD$_{(0.05)}$ between years (within row) = 707.3 kg ha^{-1}.
‡LSD$_{(0.05)}$ between years (within row) = 1296.6 kg ha^{-1}.
§Means not sharing a common letter within a column are significantly different ($P \leq 0.05$) according to Tukey's test.
¶p value for main effects and interaction.

Similar to total biomass, the harvest index (i.e., ratio of grain to total biomass) reflected the influence of rainfall, but there was no cultivar × year interaction (Table 3). In the first season (dry), the average harvest index was 0.15 while in the second season (wet) it was 0.41. The two highest harvest indices (regardless of season) were observed with the single cross hybrids ('AG9010' = 0.36 and 'DKB950' = 0.37), and the two lowest indices were in 'Palotina' (0.14) and 'GI045' (0.18).

Grain C concentration did not differ among cultivars and there was no cultivar × year interaction, but differences were observed between growing seasons (Table 4) with higher values being observed in the first season (419.8 g kg^{-1} vs. 411.5 g kg^{-1}). Nevertheless, residue C concentration (Table 4) differed significantly among cultivars and years and the cultivar × year interaction was significant. In the first season, mean residue C concentration was 430.4 g kg^{-1}, and varied from 423.0 g kg^{-1} ('Palotina') to 438.3 g kg^{-1} ('DKB950'); in the second season, the mean was 443.1 g kg^{-1}, and varied from 440.6 g kg^{-1} ('AG5020') to 448.2 g kg^{-1} ('AG9010').

Effects of cultivar, year, and cultivar × year interaction were significant for grain and residue N concentration (Table 5). The average grain N

TABLE 3 Total biomass (grain + residue) and harvest index of ten corn cultivars for the 2005/2006 and 2006/2007 growing seasons

Cultivar		Total biomass†			Harvest index		
		2005/2006	2006/2007	Mean	2005/2006	2006/2007	Mean
			kg ha^{-1}				
Single	AG9010	9795bc‡	15450bcde	12623de	0.20abc	0.52a	0.36a
Single	DKB950	8991c	15391bcde	12191e	0.23a	0.50ab	0.37a
Triple	AG5020	13652a	19359a	16505a	0.18abcd	0.46abc	0.32ab
Triple	DKB566	12282ab	16504bc	14393bcd	0.22ab	0.45bc	0.34ab
Double	AG2040	12547a	19450a	15998ab	0.15bcd	0.42cd	0.29bc
Double	DKB979	11824ab	17921ab	14872abc	0.22ab	0.45abc	0.34ab
Commercial	BRS4157	12282ab	13755de	13019de	0.14cd	0.36de	0.25c
Commercial	BR106	13259a	16145bcd	14702abc	0.11de	0.39cde	0.25c
Landrace	GI045	12810a	13294e	13052cde	0.05ef	0.32ef	0.18d
Landrace	Palotina	13661a	14333cde	13997cde	0.01f	0.28f	0.14d
	Mean	12110	16231		0.15	0.41	

ANOVA

Source of variation	df	Total biomass	Harvest index
Cultivar (C)	9	<0.0001§	<0.0001
Year (Y)	1	<0.0001	<0.0001
C × Y	9	<0.0001	0.0774
CV (%)		8.8	12.7

†$LSD_{(0.05)}$ between years (within row) = 1569.6 kg ha^{-1}.

‡Means not sharing a common letter within a column are significantly different ($P \leq 0.05$) according to Tukey's test.

§p value for main effects and interaction.

concentration in the first season was 19.12 g kg^{-1}, with the highest observed being Palotina with 21.31 g kg^{-1} and the lowest being 'DKB950' at 16.75 g kg^{-1}. In the second season, the overall cultivar grain N concentration mean was 15.78 g kg^{-1}, varying from 14.35 g kg^{-1} ('DKB566') to 17.34 g kg^{-1} ('BRS4157'). The average residue N concentrations were 11.43 g kg^{-1} in the first season and 7.46 g kg^{-1} in the second season. During the first season there was more variability in residue N concentration (60% difference between the highest and the lowest values) than in the second season (48%).

Residue C:N ratio (Table 6) showed some differences among corn cultivars, as well as between years, however the cultivar × year interaction was not significant. In the first season, the average residue C:N ratio was 38.9 and varied from 30.0 ('Palotina') to 49.9 ('AG9010'). In the second season with little drought, the average rose to 61.4 and varied from 49.6 ('Palotina') to 71.2 ('AG9010'). Averaged across years, the two highest residue C:N ratios were noted in the single cross hybrids 'AG9010' (60.6) and 'DKB950' (59.2), and the lowest ratio was noted with 'Palotina' landrace (39.8).

Grain and residue C content presented in Table 7 indicates that water stress during tasseling impacted grain C content more than residue C

TABLE 4 Grain and residue C concentrations of ten corn cultivars for the 2005/2006 and 2006/2007 growing seasons

		C concentration					
		Grain			Residue†		
Cultivar		2005/2006	2006/2007	Mean	2005/2006	2006/2007	Mean
		g kg^{-1}					
Single	AG9010	417.7a	410.5a	414.1a	437.2ab‡	448.2a	442.7a
Single	DKB950	420.1a	411.5a	415.8a	438.3a	446.0ab	442.1a
Triple	AG5020	416.6a	413.0a	414.8a	432.0bcd	440.6b	436.3b
Triple	DKB566	418.7a	408.1a	413.4a	430.5cd	440.7b	435.6b
Double	AG2040	418.3a	414.2a	416.2a	432.9abc	441.6b	437.2b
Double	DKB979	418.9a	412.4a	415.6a	430.5cd	440.8b	435.7b
Commercial	BRS4157	424.2a	413.7a	419.0a	426.8de	441.5b	434.2b
Commercial	BR106	421.7a	410.8a	416.2a	427.9cde	443.7ab	435.8b
Landrace	GI045	423.1a	411.8a	417.5a	424.4e	443.7ab	434.1b
Landrace	Palotina	418.7a	408.9a	413.8a	423.0e	443.9ab	433.5b
	Mean	419.8	411.5		430.4	443.1	

ANOVA

Source of variation	df	Grain	Residue
Cultivar (C)	9	0.0953§	<0.0001
Year (Y)	1	<0.0001	<0.0001
C × Y	9	0.3183	<0.0001
CV (%)		0.9	0.6

†$LSD_{(0.05)}$ between years (within row) = 3.6 g kg^{-1}.

‡Means not sharing a common letter within a column are significantly different ($P \leq 0.05$) according to Tukey's test.

§p value for main effects and interaction.

content. Average grain and residue C contents were 748 kg C ha^{-1} and 4436 kg C ha^{-1} in the first season, respectively, and respective values were 2789 kg C ha^{-1} and 4156 kg C ha^{-1} in the second season. Total C content (whole plant) was 5184 kg C ha^{-1} and 6945 kg C ha^{-1} in the first and second seasons, respectively (Table 8). Differences in cultivar averages of total C content were lower during the season with drought [from 3903 kg C ha^{-1} ('DKB950') to 5861 kg C ha^{-1} ('AG5020')] than in the season without this stress [from 5764 kg C ha^{-1} ('GI045') to 8364 kg C ha^{-1} ('AG2040')].

The C harvest index (Table 8) was similar to the harvest index. Differences were observed among corn cultivars and between years, but there was no cultivar × year interaction. Average C harvest indices were 0.15 and 0.40 in the first and second seasons, respectively. In the first season, this index varied from 0.01 ('Palotina') to 0.22 ('DKB950'), while in the second season the index varied from 0.26 ('Palotina') to 0.50 ('AG9010').

Pre-planned cultivar comparisons were also performed (Table 9). Single cross hybrids and landraces were compared and exhibited differences in residue C and N content, residue C:N ratio, as well as in total C content and C harvest index. Likewise, these comparisons were performed between hybrids

TABLE 5 Grain and residue N concentrations of ten corn cultivars for the 2005/2006 and 2006/2007 growing seasons

		N concentration					
		Grain†			Residue‡		
Cultivar		2005/2006	2006/2007	Mean	2005/2006	2006/2007	Mean
		g kg^{-1}					
Single	AG9010	16.96de§	15.09cd	16.03d	8.85e	6.36c	7.61d
Single	DKB950	16.75e	15.25cd	16.00d	9.13de	6.40bc	7.77d
Triple	AG5020	19.72abc	15.09cd	17.40c	11.92abc	6.49bc	9.21bcd
Triple	DKB566	17.51de	14.35d	15.93d	10.14cde	7.21abc	8.68cd
Double	AG2040	20.56ab	15.81abcd	18.19abc	11.49bcd	6.70bc	9.10bcd
Double	DKB979	19.60bc	15.79abcd	17.70bc	10.42cde	7.52abc	8.97cd
Commercial	BRS4157	19.85abc	17.34a	18.60ab	12.81ab	8.68abc	10.74ab
Commercial	BR106	20.30ab	15.68bcd	17.99bc	11.86abc	7.08abc	9.47bc
Landrace	GI045	18.62cd	16.39abc	17.50bc	13.53ab	8.75ab	11.14a
Landrace	Palotina	21.31a	17.02ab	19.16a	14.12a	9.41a	11.76a
	Mean	19.12	15.78		11.43	7.46	

ANOVA

Source of variation	df	Grain	Residue
Cultivar (C)	9	<0.0001¶	<0.0001
Year (Y)	1	<0.0001	<0.0001
C × Y	9	<0.0001	0.0028
CV (%)		4.6	12.1

†LSD$_{(0.05)}$ between years (within row) = 1.0 g kg^{-1}.
‡LSD$_{(0.05)}$ between years (within row) = 1.4 g kg^{-1}.
§Means not sharing a common letter within a column are significantly different ($P \leq 0.05$) according to Tukey's test.
¶*p* value for main effects and interaction.

and commercial varieties. Significant differences were observed between these groups of cultivars and their implications are discussed below.

DISCUSSION

The results indicated that there was a difference among cultivars for total biomass in both years studied (Table 3). However, it was not possible to confirm that total biomass differences were related to cultivar technological level. In contrast, differences in technological level were observed for grain and residue when viewed separately. Commercial varieties and landraces had higher residue production compared to hybrids while higher grain yield was directly associated with technological level (Table 2).

The consequences of breeding efforts were reflected in harvest indexes that mirrored the technological level (Table 3). Vieira Junior et al. (2005) indicated that advances in yield of important cultivated crops did not arise from improvement in photosynthetic efficiency, but from allocation of photoassimilates to crop fractions of economic interest (i.e., grain). This also demonstrated why total biomass differed little between older and modern

TABLE 6 Residue C:N ratio of ten corn cultivars for the 2005/2006 and 2006/2007 growing seasons

Cultivar		Residue C:N ratio 2005/2006	2006/2007	Mean
Single	AG9010	49.90a	71.22a	60.56a†
Single	DKB950	48.22a	70.10a	59.16ab
Triple	AG5020	36.66abc	68.51a	52.58ab
Triple	DKB566	42.57abc	62.08abc	52.32abc
Double	AG2040	38.04abc	67.04a	52.54ab
Double	DKB979	41.52abc	59.05abc	50.29bcd
Commercial	BRS4157	33.80c	51.81bc	42.80cde
Commercial	BR106	36.33bc	63.29ab	49.81bcd
Landrace	GI045	31.72c	51.39bc	41.56de
Landrace	Palotina	30.03c	49.60c	39.81e
	Mean	38.88	61.41	

ANOVA

Source of variation	df	
Cultivar (C)	9	<0.0001‡
Year (Y)	1	<0.0001
C × Y	9	0.1889
CV (%)		13.1

†Means not sharing a common letter within a column are significantly different ($P \leq 0.05$) according to Tukey's test.

‡p value for main effects and interaction.

cultivars (Duvick, 1992). Our findings indicate that corn genetic development favored grain yield, thus yielding greater economic return at the farm level. However, these efforts decreased the proportion of residue that can be used for soil coverage, cattle food, or biomass for energy (Pordesimo et al., 2004; Varvel et al., 2008).

If crop improvement results in more leaf area, mean leaf photosynthetic rate may decline because of increased self-shading, and maximum leaf photosynthetic rates may decline because resources are spread more thinly across the larger leaf area (Evans, 1993). Sink-source studies with corn have shown that reproductive sink capacity is commonly a limiting factor for grain yield in corn in temperate and subtropical regions, and that grain yield improvement may be achieved by selecting for factors that increase the assimilate supply to the ear (Tollenaar, 1977; Pimentel, 1998). Hence, photosynthesis can be limited by sink capacity (i.e., ability to use photosynthate; Long et al., 2006), which may explain why cultivars with higher shoot biomass production do not necessarily produce more grain as shown in our study. On the other hand, the results from 'AG5020' and 'AG2040' indicated that the breeding process can increase crop yield without compromising the amount of crop residue left in the field.

For residue C concentration, the main effect of drought (or year) was significant (Table 4) and adequate rainfall during tasseling increased this measure (3.0%). Carbon dioxide assimilation by leaves is reduced mainly

TABLE 7 Grain (output) and residue C content (input) of ten corn cultivars for the 2005/2006 and 2006/2007 growing seasons

		C content					
		Grain†			Residue‡		
Cultivar		2005/2006	2006/2007	Mean	2005/2006	2006/2007	Mean
		kg C ha^{-1}					
Single	AG9010	830ab§	3298ab	2064a	3413de	3323d	3368d
Single	DKB950	875ab	3178b	2027a	3027e	3420cd	3224d
Triple	AG5020	1018ab	3668a	2343a	4844abc	4616ab	4730ab
Triple	DKB566	1167a	3008bc	2087a	4086cd	4025bcd	4056c
Double	AG2040	801ab	3406ab	2104a	4602bc	4958a	4780ab
Double	DKB979	1101a	3357ab	2229a	3959cd	4312abc	4135bc
Commercial	BRS4157	741abc	2042d	1391b	4496bc	3895bcd	4196bc
Commercial	BR106	613bc	2564c	1588b	5053ab	4395ab	4724ab
Landrace	GI045	258cd	1740d	999c	5178ab	4024bcd	4601abc
Landrace	Palotina	81d	1630d	856c	5699a	4593ab	5146a
	Mean	748	2789		4436	4156	

ANOVA

Source of variation	df	Grain	Residue
Cultivar (C)	9	<0.0001¶	<0.0001
Year (Y)	1	<0.0001	0.0026
C × Y	9	<0.0001	0.0002
CV (%)		13.2	10.4

†LSD$_{(0.05)}$ between years (within row) = 295.4 kg C ha^{-1}.
‡LSD$_{(0.05)}$ between years (within row) = 565.6 kg C ha^{-1}.
§Means not sharing a common letter within a column are significantly different ($P \leq 0.05$) according to Tukey's test.
¶*p* value for main effects and interaction.

by stomatal closure, membrane damage, and disturbed activity of various enzymes, especially those of CO_2 fixation and adenosine triphosphate synthesis (Farooq et al., 2009). Even a mild drought may affect corn production by inducing stomatal closure thereby decreasing water loss and absorption of CO_2 via photosynthesis (Hsiao, 1973; Durães et al., 2004). This results in the crop making use of previously accumulated reserves (Pimentel, 1998). Bänziger et al. (2000) suggested that additional reductions in crop production may come from increased energy and nutrient consumption due to adaptive drought responses (e.g., increased root growth). Drought conditions may also lead to remobilization of C reserves from leaves and stalks tissues to support kernel mass during grain filling. After number of kernels per ear is established, kernel growth will be supported by current photosynthesis and/or by remobilization of C and N reserves to support physiological seed quality (Galbiatti et al., 2004). Westgate (1994) reported that rates of dry matter accumulation in kernels were not reduced under water stress conditions after anthesis, which was likely due to reserve remobilization from leaves and stalks. Clearly, assimilate translocation to reproductive sinks is

TABLE 8 Total C content and C harvest index of ten corn cultivars for the 2005/2006 and 2006/2007 growing seasons

Cultivar		Total C content† (kg C ha^{-1})			C harvest index		
		2005/2006	2006/2007	Mean	2005/2006	2006/2007	Mean
Single	AG9010	4243bc‡	6621bcd	5432de	0.195abc	0.499a	0.347a
Single	DKB950	3903c	6598bcd	5250e	0.223a	0.481a	0.352a
Triple	AG5020	5861a	8284a	7073a	0.175abcd	0.443ab	0.309ab
Triple	DKB566	5253ab	7033bc	6143bcd	0.219ab	0.427abc	0.323ab
Double	AG2040	5403a	8364a	6884ab	0.150bcd	0.408bcd	0.279ab
Double	DKB979	5060ab	7668ab	6364abc	0.216ab	0.438abc	0.327bc
Commercial	BRS4157	5237ab	5937cd	5587cde	0.141cd	0.344de	0.243c
Commercial	BR106	5666a	6959bc	6312abc	0.107de	0.370cde	0.239c
Landrace	GI045	5436a	5764d	5600cde	0.048ef	0.303ef	0.176d
Landrace	Palotina	5780a	6223cd	6002cde	0.013f	0.260f	0.137d
	Mean	5184	6945		0.149	0.398	

ANOVA

Source of variation	df	Total C content	C harvest index
Cultivar (C)	9	<0.0001§	<0.0001
Year (Y)	1	<0.0001	<0.0001
C × Y	9	<0.0001	0.0705
CV (%)		8.9	12.9

†LSD$_{(0.05)}$ between years (within row) = 677.1 kg C ha^{-1}.
‡Means not sharing a common letter within a column are significantly different ($P \leq 0.05$) according to Tukey's test.
§p value for main effects and interaction.

vital for seed development (Farooq et al., 2009). Collectively, these factors may help explain why corn cultivars had lower residue C concentration and higher grain C concentration in the first season when drought stress occurred during tasseling.

TABLE 9 Pre-planned group of cultivars comparisons for residue C and N concentration (g kg^{-1}), C:N ratio, total C content (kg C ha^{-1}) and C harvest index for the 2005/2006 and 2006/2007 growing seasons

Variable	Comparison†	2005/2006	p‡	2006/2007	p
Residue C concentration	SHY vs. LR	437.7 vs. 423.7	<0.0001	447.1 vs. 443.8	0.0049
	HY vs. CV	433.5 vs. 427.4	0.0001	443.0 vs. 442.6	0.7905
Residue N concentration	SHY vs. LR	8.99 vs. 13.82	<0.0001	6.38 vs. 9.08	0.0002
	HY vs. CV	10.33 vs. 12.33	0.0005	6.78 vs. 7.88	0.0035
Residue C:N ratio	SHY vs. LR	49.06 vs. 30.88	<0.0001	70.66 vs. 50.50	<0.0001
	HY vs. CV	42.82 vs. 35.07	0.0007	66.33 vs. 57.55	0.0089
Total C content	SHY vs. LR	4073 vs. 5608	<0.0001	6609 vs. 5994	0.0199
	HY vs. CV	4954 vs. 5451	0.0746	7428 vs. 6448	0.0035
C harvest index	SHY vs. LR	0.21 vs. 0.03	<0.0001	0.49 vs. 0.28	<0.0001
	HY vs. CV	0.20 vs. 0.12	0.0003	0.45 vs. 0.36	<0.0001

†CV, commercial varieties; HY, hybrids; LR, landraces; SHY, single cross hybrids.
‡Pre-planned group of cultivars comparisons were analyzed using Student's t statistic.

Grain N concentration (Table 5) was slightly higher (21.2%) in the first season that experienced water stress during tasseling. Jurgens et al. (1978) reported that water stress increased grain protein concentration by ~33% but decreased oil concentration by ~18%. In contrast, Westgate (1994) noted no discernible water stress effect on kernel composition. Reed et al. (1980) studying four corn hybrids under non-limiting field conditions found variation among genotypes for grain, leaf, and stalk N concentration which was similar to our observations. Ta and Weiland (1992) observed variations among genotypes in corn residue N content and its importance for remobilization during kernel development. Silva (2005) observed increased total-N levels in corn stalks and increased nitrate and free amino acid content in leaves and stalks under water deficit in greenhouse conditions. The uncertainty of the influence of pre-anthesis drought affecting N grain concentration was demonstrated by Feil et al. (2005). They reported opposite responses to drought in consecutive years for the four tropical corn varieties investigated.

In general, the grain N concentration was smaller for single and triple cross hybrids than landraces confirming a trend reported by Feil et al. (2005) in the study of tropical corn. In contrast, Vyn and Tollenaar (1998) found enhancement of grain N in temperate corn. However, they also reported differences in nutrient concentration for grain among hybrids within an era could be larger than across different eras of release; this appears to be true in our study, especially in regards to the commercial and landrace varieties.

Residue C:N was 58% higher in the second season (non-drought year; Table 6), which could be attributed to the small C concentration increase (Table 4) combined with the large decrease in N concentration (Table 5). There was genotypic variation for C:N (e.g., a 52% increase in the 'AG9010' single cross hybrid vs. the Palotina landrace). Single cross hybrids were compared to the average residue C:N of landraces under the presence or absence of drought (Table 9). In these comparisons, single cross hybrids showed higher residue C:N due to higher residue C concentration and lower residue N concentration. Likewise, when hybrids were compared to commercial varieties, the C:N of hybrids was higher; however, in the absence of water stress, there was no difference in residue C and C:N was higher because of lower residue N concentration. These variations suggest that residue C:N can be influenced by classes of organic compounds in plant tissues (i.e., cellulose, hemicellulose, starches, proteins, lipids, and polyphenols), which genetically differ among species and may possibly vary within a species. The observed variations also suggest that breeding selection (primarily for yield improvement) resulted in hybrids having a higher residue C content and a lower residue N content, resulting in increased residue C:N.

In a recombinant inbred line population, Cardinal et al. (2003) did genetic mapping to estimate the effects of quantitative trait loci that affect cell-wall components (especially fiber and lignin content) in the leaf-sheath and stalk of corn. After five cycles of selection for high and low stalk crushing strength, Undersander et al. (1977) found no change in lignin content in corn stalks derived from either of two source populations; they concluded that stalk strength and lodging resistance can be increased with little effect on stalk composition. In three populations based on individuals selected for extremely divergent fiber concentration, Wolf et al. (1993) showed only weak and inconsistent correlations between lignin content and various agricultural fitness parameters (height, grain yield, total yield, lodging, days to silk). In contrast, our study showed a wide range in plant residue C and N concentration (Tables 4 and 5), possibly indicating differences in organic tissue compounds among cultivars.

Carbon and N concentrations have been extensively used as indicators of residue quality (Jawson and Elliot, 1986; Taylor et al., 1989; Wagger et al., 1998; Martens, 2000; Nicolardot et al., 2001; Hadas et al., 2004; Prior et al., 2004, 2006), since decomposition rate is inversely related to tissue C:N. With the widespread adoption of no-tillage systems, primary importance has been placed on maintaining crop residues on the soil surface. This reinforces the need of producing plant residues that slowly decompose thereby protecting the soil for longer periods (Ceretta et al., 2002). Materials that slowly decompose complement the time needed for soil aggregation to occur (Martin, 1942). Cantarella et al. (2005) suggested the adoption of crops that produce high biomass and have high C:N ratio for soil protection in the dry winter regions of Brazil (e.g., Cerrados and northern Sao Paulo State). In corn-based agroecosystems, single cross hybrids or hybrids (vs. commercial varieties and landraces) may meet these needs due to greater production and higher residue C:N ratio. However, changes in residue quality (as reflected by higher C:N) may decrease residue digestibility when used for animal consumption in integrated farming systems. Such shifts in residue quality may also indicate a high energetic power when these residues are used as a fuel source. Further, changes in residue C:N ratio may promote N immobilization, therefore subsequent crops may require additional N fertilization; this may be especially true for crops following hybrids.

Differences in total C content were noted (Table 7). However, there was little difference in grain C concentration among cultivars (Table 4). Therefore, grain contribution to total C content was due to quantity of grain rather than changes in grain C concentration. On the other hand, residue C content was affected by both the amount of residue produced and its C concentration. Comparisons between single cross hybrids and landraces (Table 9) showed that total C content of total biomass for landraces were higher under drought conditions (first season) compared to the single cross hybrids; however, this pattern was reversed under non-limiting water (second season). In the other comparisons between hybrids and commercial varieties, total C content was higher in hybrids except under water stress conditions. It is important to note that the severe drought that occurred in 2005/2006 was unusual and that the results from 2006/2007 are more typical of growth conditions that farmers face.

The C harvest index (Table 8) indicates how much C in the total biomass was allocated to grain. In other words, this index represents the partitioning of total C between grain and non-yield residue components (not including root biomass). For example an index of 0.40 (i.e., the overall cultivar mean in 2006/2007), indicated that 40% of the C was allocated to grain or that for each kilogram of C in total biomass, approximately 400 g was in grain. As expected, under water deficit conditions, this index was lower (0.15) showing that the index was influenced more by residue C. The results from Table 8 not only show hybrids 'AG5020' and 'AG2040' to be top grain and residue producers, but also indicated they have a higher C sink capacity compared to landraces. Furthermore, although a large proportion of corn grain production is for animal and human consumption, a wide range of other products are derived from corn for different industrial activities, such as chemical, pharmaceutical, metallurgical, paper and cellulose, and textile (Paes, 2006). Consequently, the quantification of grain C content and a more detailed tracing of the grain trail within the industrial production chain are required to more accurately predict if industries are sources of C outputs to the atmosphere or producing products that are sinks of C.

Pre-planned C harvest index comparisons between single cross hybrids and landraces (Table 9) showed that single cross hybrids had higher indices. Similarly, hybrids were higher than commercial varieties. Considering the overall mean C harvest index by cultivar (regardless of year; Table 8), it was possible to rank the groups as follows: single cross hybrids > double cross hybrids = triple cross hybrids > commercial varieties > landraces. Not surprising, our findings suggest that the breeding selection process resulted in corn hybrids having higher C grain content. Furthermore, as previously discussed, residues with more C represents inputs to the soil that could help maximize the benefits of no-tillage and promote soil C sequestration. It is important to note that our study did not evaluate the contributions of the root system that can have an important impact on C sequestration in soil. Machinet et al. (2009) evaluated roots from four corn lines and two hybrids and observed significant differences in their C and N content and chemical characteristics of root residues.

CONCLUSIONS

Under diverse weather conditions, corn genotypes displayed differences in residue C and N and their respective C:N ratios. Crop residues normally remain in the field following harvest and shifts in quality may impact their decomposition. In general, single cross hybrids concentrated more C in vegetative biomass and corresponding C:N ratios were higher. This suggests that these residues may decompose more slowly, thereby physically protecting the soil for longer time periods. In contrast, the lower residue C:N ratios of landraces may lead to faster residue decomposition. In general, drought conditions may result in lower C:N ratios. Drought can decrease photosynthetic assimilation, increase energy consumption for adaptive responses, and cause remobilization of energy reserves to source regions such as seeds. This reallocation helps explain the small difference in overall grain C concentration observed under varying rainfall conditions.

Carbon content reflected grain and shoot biomass responses and corresponding changes in respective C concentration. There was little difference among cultivars in grain C concentration, thus changes in grain C content were primarily due to increases in grain mass. In general, hybrids can store C in residues as much as landraces (in a drought year) or more than landraces under adequate rainfall conditions. Higher C harvest indices for single cross hybrids reflected greater C allocation to grain, while lower indices for landraces reflected more C allocation to non-yield residues (roots were not considered).

Genotypic variations (within variables analyzed) indicated that breeding selection, which aimed to improve grain yield, may have resulted in corn cultivars with different residue compositions. Based on our results, the top yielding hybrids (i.e., AG5020, DKB979, and AG2040) are recommended for use in this region. Compared to the older cultivars (commercial varieties and landraces), these hybrids can produce adequate residue for soil health without compromising yield. Findings suggest that the breeding process can select plants that increase grain yield and the amount and quality of residue returned to soil.

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