The interaction of drought stress and heat stress as determinant of dry matter yield and nutritional composition of maize (Zea mays L) whole-plant for silage

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Abstract

The objective of this study was to understand how abiotic factors affected dry matter (DM) yield and nutritional composition of maize whole-plant for silage. We analyzed data from maize hybrids performance trials completed at two sites (ie, Southern Piedmont and Shenandoah Valley regions) during 2011 and 2012. Data from eight maize hybrids (110 to 117 days to maturity) were tested in both sites and years. Dry matter yield and nutritional composition were analyzed through mixed model analysis. Climate data were obtained from weather stations located in Blackstone and Elkton (Virginia, USA). Whole-plant DM yields varied significantly across site.years ($P < 0.01$), ranging from 4,556 to 15,092 kg ha^{-1}. Dry matter (DM; $P < 0.01$) and crude protein (CP; $P < 0.01$) concentrations differed among site.years. These high variations are attributed to the low DM concentration (25.3% DM) and to the high CP concentration (10.9% CP) observed for the Southern Piedmont region in 2012. Neutral detergent fiber (NDF; $P < 0.01$) and acid detergent fiber (ADF; $P < 0.01$) were significantly different between site.years. That NDF concentration in 2012 was substantially lower for the Shenandoah Valley region (43.0% NDF) than for the Southern Piedmont region (56.6% NDF) indicates that maize crops were affected differently despite summer drought. We concluded that heat stress had a major adverse effect on kernel development in the Southern Piedmont region, but not in the Shenandoah Valley region, and that heat stress exacerbated the effects of drought reducing substantially DM yields and increasing whole plant fiber concentration.

Keywords: drought stress, heat stress, maize silage, forages, climate change

Abbreviations: ADF = acid detergent fiber, CP = crude protein, DM = dry matter, GDD = growing-degree days, NDF = neutral detergent fiber

Introduction

Whole-plant maize silage is a major ingredient in diets for dairy cattle. Therefore, producing high yielding and good quality forage is critical for minimizing production costs in dairy farming systems. Different management practices or genotype selections can affect yield and quality of maize whole-plant for silage. Whole-plant DM yields can be increased with higher planting densities (Cusicanqui and Lauer, 1999; Ferreira et al, 2014) or nitrogen fertilization rates (Roth et al, 2013). Increasing maize plant density may increase fiber concentration and decrease in vitro dry matter (DM) digestibility of maize whole-plant (Cusicanqui and Lauer, 1999), due to a lower grain to stover ratio (Roth et al, 2013). Delaying harvesting time also increases DM yields and reduces fiber concentration of maize whole-plant (Bal et al, 1997; Ma et al, 2006), although nutrient utilization can be diminished if kernel processors are not utilized when chopping at late maturity stages (Ferreira and Mertens, 2006). Increasing cutting height at harvesting reduces fiber and lignin concentrations of maize whole-plant (Kung et al, 2008), although this reduces DM yields by 7.4 to 16.7% (Wu and Roth, 2003; Kung et al, 2008). As regard to genotype selection, planting maize hybrids with the brown midrib 3 mutation results in whole-plant maize silages with greater in vitro neutral detergent fiber (NDF) digestibility (Oba and Allen, 2000; Taylor and Allen, 2005), although DM yield is typically inferior for these hybrids (Lee and Brewbaker, 1984; Bal et al, 2000). Despite these multiple controllable factors, uncontrollable environmental factors can affect DM yield and composition of maize whole-plant for silage (NeSmith and Ritchie, 1992; Çakir, 2004; Castro-Nava et al, 2014; Ferreira et al, 2014). Drought stress reduces maize whole-plant DM yields, particularly when it occurs during the reproductive stages of the crop (NeSmith and Ritchie, 1992; Çakir, 2004). In terms of forage composition, drought stress likely reduces grain to stover ratio of maize whole-plant (NeSmith and Ritchie, 1992; Çakir, 2004), therefore increasing fiber concentrations. Contrary to this, abundant precipitations (>700 mm)

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avoided changes in maize whole-plant composition typically seen when maize is planted at increased plant densities (Ferreira et al, 2014). The spring and summer drought of 2012 will be remembered as one of the «worst agricultural calamities» in the United States (USDA, 2013). The drought of 2012 reduced the national maize grain and silage yields by 16.2 and 16.3%, respectively, when compared to 2011 (USDA, 2013). Maize hybrid performance trials completed in four locations across the state of Virginia (Behl et al, 2011; Behl et al, 2012) showed that climate affected DM yields differently. Indeed, whole-plant DM yields ranged from 4,805 to 18,368 kg ha^{-1} in 2012 and from 12,148 to 17,110 kg ha^{-1} in 2011. Similarly, whole-plant NDF concentrations ranged from 43.8 to 55.8% in 2012, but 48.6 to 53.8% in 2011. These observations suggest that the spring and summer drought in 2012 affected maize whole-plant DM yield and composition in different ways. The objective of this retrospective study was to better understand how climate factors affected DM yield and nutritional composition of maize whole-plant destined for silage.

Materials and Methods

Selected Sites and Hybrids

This study was based on data from maize hybrids performance trials completed at four sites over two growing seasons within the state of Virginia (Behl et al, 2011; 2012). Due to limited climate information, data from only two of the four sites in each of two years were analyzed. The first site is known as the Southern Piedmont region and was located in Blackstone, VA (37°05’41”N and 77°57’50”W). The second site is known as Shenandoah Valley region and was located in Lynnwood, VA (38°18’49”N and 78°45’45”W). Soil series and classifications from the experimental areas are Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult) and Allegheny fine sandy loam (fine-loamy, mixed, semiactive, mesic, Typic Hapludults) at Southern Piedmont and Shenandoah Valley, respectively. Data from only eight maize hybrids, which were tested in both sites and years, were used in the analysis. All hybrids had 110 to 117 days to maturity. The estimated growing-degree days (GDD) to silking ranged from 1,360 to 1,450 GDD, with an average of 1,410 GDD. Cumulative GDD were estimated using maximum and minimum temperatures according to Neild and Newman (1987).

Cultural Management

The preceding crop was soybean at the Southern Piedmont site and maize at the Shenandoah Valley site in both years. Hybrids were planted in two-row plots, 7.6 meters long with 0.76 meters between rows. All hybrids were replicated four times at each site. All sites were planted with a Wintersteiger Plot-King 2600 planter (Wintersteiger Inc, Salt Lake City, UT) at a seeding rate of 69,100 plants per hectare. Whole plants were harvested by hand and chopped with a chipper/shredder at Southern Piedmont and with a commercial silage harvester without kernel processing at Shenandoah Valley. The entire plot length from two rows was harvested and weighed in each case. A subsample of the fresh chopped material was collected from each plot and kept on ice until frozen. Samples were then dried at 50°C in a forced air-drying oven until constant moisture was reached. Samples were then weighed to determine DM content of the field-moist samples. After drying, samples were ground to pass a 2-mm screen of a Willey mill (Arthur H Thomas, Philadelphia, PA) and analyzed with near infrared spectroscopy using an XDS Rapid Content Analyzer (Foss NIR Systems, Inc Laurel, MD).

Climate Data and Growing-degree Days

Data for daily maximum and minimum temperatures and precipitations were obtained from weather stations located in Blackstone and Elkton, VA. The Shannon Diversity Index (Table 1), which describes the distribution of rainfalls for a certain period, was estimated as described by Bronikowski and Webb (1996). A diversity index equal to 0 implies complete unevenness (i.e., all rain in one day) and an index equal to 1 implies complete evenness (i.e., equal amounts of rain throughout all days).

Table 1 - Planting and harvesting dates, and rainfalls of experimental maize plots from the Southern Piedmont and Shenandoah Valley regions in Virginia during 2011 and 2012.

	Southern Piedmont		Shenandoah Valley	
	2011	2012	2011	2012
Planting date	April 18	April 10	May 6	May 21
Harvesting date	August 31	July 17	August 24	September 12
Growing period, days	136	119	111	125
Rainfalls, mm	500.9	227.6	280.4	262.4
April	12.7	71.9	0	0
May	103.4	65.8	86.1	61.2
June	92.2	27.2	82.6	37.1
July	138.9	62.7	34.0	65.8
August	153.7	0	77.7	78.5
September	0	0	0	19.8
Rainfall Shannon Diversity Index	0.65	0.66	0.60	0.67

Statistical Analysis

To evaluate sources of variation in DM yield and composition, data were analyzed using the MIXED Procedure of SAS 9.2 (SAS Institute Inc, Cary, NC) as for a complete block design in which hybrids were considered as treatments and site.years were considered as blocks. Each of the site.years values for yield and composition (Table 2) are from four replications in the field. The model included the fixed effect of treatments (df = 7), the random effect of blocks or site.years (df = 3) and the residual error (df = 21). The variability among blocks was tested using the likelihood ratio statistic as described by Littell et al (1996). Briefly, we estimated the difference between the -2 Res Log Likelihood of the model containing the random effect of block and the model without the random effect of block. The P-value for the resulting difference was obtained from a chi-squared distribution with 1 degree of freedom.

Results and Discussion

Whole-plant DM yields did not differ between hybrids ($P < 0.68$), but varied significantly across sites. years ($P < 0.01$, Table 2). Based on rainfalls (Table 1) we would have not expected the second lowest DM yield (12,482 kg DM ha^{-1}) in the Southern Piedmont area for 2011, the site.year with the greatest amount of rainfalls (Table 2). Rainfalls in the Shenandoah Valley were not abundant in either year. Therefore, lower DM yield in the Southern Piedmont may reflect inferior soil quality or fertility compared to the Shenandoah Valley. The Virginia Agricultural Land Use Evaluation System (Donohue et al, 1994) recognizes this fact and estimates the yield potential of the soil at the Shenandoah Valley site to approximately 15% higher than the yield potential at the Southern Piedmont site. The extremely low DM yield observed for the Southern Piedmont region in 2012 (4,556 kg DM ha^{-1}) is attributed to the severe drought suffered that year. However, precipitations in the Shenandoah Valley region were not much more abundant than for the Southern Piedmont region that year (262 and 227 mm, respectively). This observation suggests that factors other than drought stress also affected DM yield in the Southern Piedmont region in 2012. Dry matter concentration differed significantly among hybrids ($P < 0.01$) and site.years ($P < 0.01$). The high variation for DM concentration among site years is attributed to the low DM concentration (25.3% DM) observed for the Southern Piedmont region in 2012, likely due to the a reduced proportion of grain component in the whole plant. Similarly to DM concentration, CP concentration differed significantly among hybrids ($P < 0.05$) and site.years ($P < 0.01$). The high variation for CP concentration among site.years is attributed to the high CP concentration (10.9% CP) observed for the Southern Piedmont region in 2012. In agreement with the observed DM concentration, a greater proportion of vegetative tissues in the whole plant, due to a reduced grain component, can explain the observed high concentration of CP for the Southern Piedmont region in 2012. Neutral detergent fiber ($P < 0.99$) and ADF ($P < 0.75$) concentrations did not differ among hybrids, but were significantly different between site.years ($P < 0.01$, Table 2). That NDF concentration in 2012 was substantially lower for the Shenandoah Valley region (43.0% NDF) than for the Southern Piedmont region (56.6% NDF) indicates that maize crops were affected differently despite summer drought. Fiber concentration in whole-plant maize silage is highly and negatively correlated to starch concentration (Ferreira and Mertens, 2005). It is likely that kernel development explains the difference in NDF concentrations between these regions for 2012. An inferior kernel development for the Southern Piedmont region during 2012 is also supported by the low DM concentration (25.3% DM) and the relatively high CP concentration (10.9% CP) of the whole-plant (Table 2). Rainfall distribution was similar between regions for 2012, as reflected by the Shannon Diversity Index (Table 1). After plotting cumulated rainfalls against growing-degree days (Figure 1) we observed that the Southern Piedmont region had greater rainfalls than the Shenandoah Valley region for a same stage of development for the crop (i.e., growing-degree units). From the perspective of water status, these observations suggest that the Southern Piedmont region had similar water status at the same fenological stage than the Shenandoah Valley region. Therefore, poor kernel development might have been the determinant of the high fiber concentration in the Southern Piedmont region during 2012. Heat stress during kernel development can greatly affect maize grain yield (Hanft and Jones, 1986; Cheikh and Jones, 1994). Kernel development is divided by a lag phase with little kernel growth and a

Table 2 - Dry matter yield and nutritional composition† of maize hybrids tested at Southern Piedmont and Shenandoah Valley regions in Virginia during 2011 and 2012.

	Southern Piedmont		Shenandoah Valley			P <	
	2011	2012	2011	2012	SEM	Hybrid	Site.Year
DM Yield, kg ha^{-1}	12,482	4,556	15,092	12,678	2,531	0.68	0.01
DM, %	370	253	326	354	29	0.01	0.01
CP, %	87	109	77	71	9	0.05	0.01
NDF, %	515	566	528	430	31	0.99	0.01
ADF, %	309	341	305	253	19	0.75	0.01

†DM = dry matter concentration (as fed basis); CP = crude protein concentration (DM basis); NDF = neutral detergent fiber concentration (DM basis); ADF = acid detergent fiber concentration (DM basis).

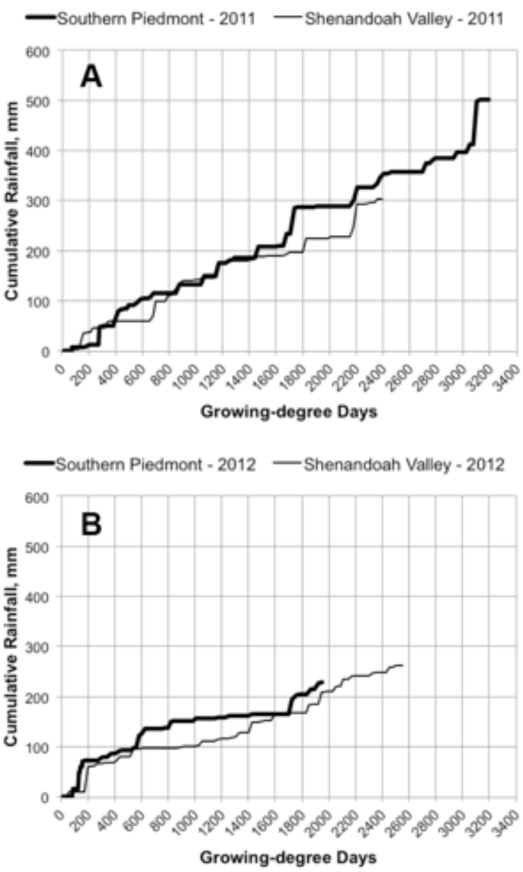

Figure 1 - Cumulated precipitations at different phenological stages of maize crops grown at two regions during 2011 (A) and 2012 (B) in the state of Virginia. Thick and thin lines represent the cumulated precipitations for the Southern Piedmont and Shenandoah Valley regions, respectively.

linear growing phase with major accumulation of DM. The lag phase, which starts immediately after pollination and lasts 10 to 12 days after pollination, is critical for kernel development (Cheikh and Jones, 1994). The endosperm is the structure of the maize kernel that contains starch granules. Cell division of the endosperm cells during the lag phase determines the capacity of the endosperm to accumulate starch within the grain (Cheikh and Jones, 1994). Cheikh and Jones (1994) cultured maize kernels *in vitro* at different temperatures and observed that heat stressed kernels (ie, kernels cultured at 35°C) accumulated 18% to 75% less DM than non-stressed kernels (ie, kernels cultured at 25°C). Reduced DM accumulation can be related to reductions in starch synthesis within the endosperm when kernels are subjected to temperatures greater than 35°C (Hanft and Jones, 1986). In addition to reduced kernel growth, Cheikh and Jones (1994) reported 23% to 97% kernel abortion when subjected to heat stress. Under the assumption that silking occurred at 1,400 growing-degree days (Neild and Newman, 1987), we accessed maximum and minimum daily temperatures records and estimated the date at which pollination occurred (Figure 2). In 2012, the Southern Piedmont region had maximum daily temperatures above 35°C for an extended period (11 days) after silking (Figure 2C), whereas maximum daily temperatures were 7.1 ± 2.3°C lower in the Shenandoah Valley region around silking (Figure 2D). It is therefore likely that heat stress had a major effect on kernel development in the Southern Piedmont region, but not in the Shenandoah Valley region. Therefore, in the Southern Piedmont region, heat stress exacerbated the effects of drought reducing substantially DM yields. Environmental factors, such as precipitation and temperature, are uncontrollable and unrepeatable, and therefore they are considered random factors. Heat stress around silking occurred in only one site.years in this retrospective study. Because this effect cannot be replicated under field conditions, our conclusions are based on variance components analysis for the observed site.

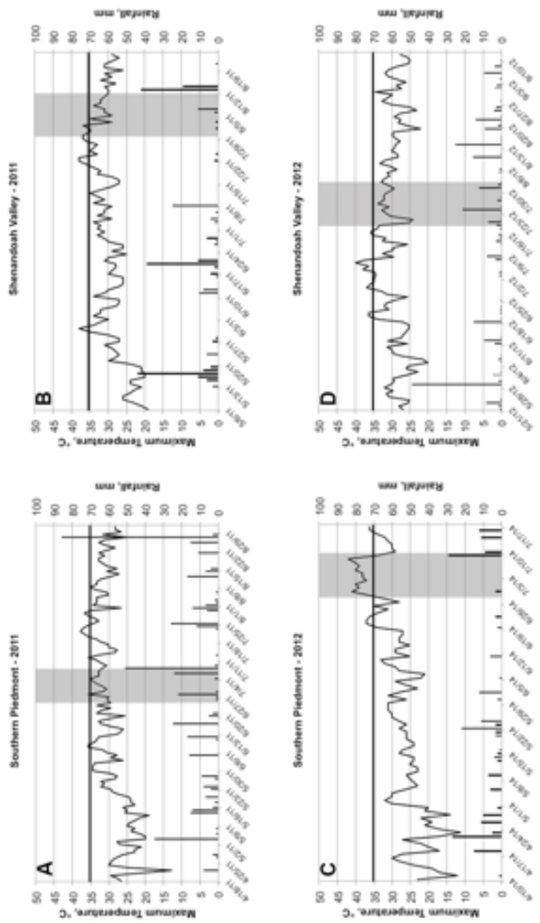

Figure 2 - Maximum daily temperatures (line) and rainfalls (columns) during the crop cycle at two regions during 2011 and 2012 in the state of Virginia. The shaded region represents the critical stage for kernel development. The thick horizontal line represents the threshold temperature for heat stress (>35°C). Prolonged heat stress after silking occurred only in the Southern Piedmont region during 2012, but not in other site years[-1].

Table 3 - Planting and harvesting dates, and rainfalls of experimental maize plots from four regions in Georgia during 2012.

	Blairsville	Calhoun	Griffin	Tifton
Planting date	May 1	April 11	April 2	March 28
Harvesting date	September 7	August 23	August 17	July 26
Growing period, days	130	135	138	121
Rainfalls†, mm	445	429	388	420
Supplemental irrigation	No	Yes	Yes	Yes

† Rainfalls do not account irrigated quantities.

years (ie, random effect of blocks). To better support our conclusions we revised maize hybrid tests results for year 2012 from Georgia (Coy et al, 2012; Table 3), New York (Cox et al, 2012), North Carolina (Bowman, 2012), Pennsylvania (Roth et al, 2012), Tennessee (Allen and Johnson, 2012) and Wisconsin (Lauer et al, 2012). From these states, high temperatures (ie, > 35°C) around silking seemed to occur only in Georgia and Tennessee (data not reported). The maize silage trial from Tennessee reported neither nutrient composition nor grain to stover ratio, and therefore was not further analyzed. Using the same statistical analyses as for Virginia, we determined variance components for DM yield and grain to stover ratio (Table 4) using 15 mid-season hybrids grown in four sites from Georgia in 2012 (Coy et al, 2012), and observed that DM yield and grain to stover ratio varied significantly across sites ($P < 0.01$). After collecting weather data from the Georgia Automated Environmental Monitoring Network (2012) we observed that grain yield and grain to stover ratio were lower when heat stress occurred around silking despite irrigation (site Calhoun). In addition to this, grain to stover ratio was not reduced when the theoretical lag phase of kernel development occurred before heat stress (site Griffin). Observations from these sites in Georgia further support that heat stress around silking has a major impact on kernel development and, therefore, can greatly affect whole-plant maize silage quality beyond water status. The observations from this study have major practical implications. In first instance, heat stress may affect the nutritional composition of maize silage even in crops with adequate water status. Similar to the data reported in this study, Ferreira observed concentrations of 28.1% DM, 11.6% CP, and 59.9% NDF for maize silage originated from an irrigated maize field suffering heat stress immediately after pollination (unpublished observations), suggesting that silage quality is not assured exclusively by water status. Dairy farmers, agronomists, and dairy consultants should also not overlook the regional temperatures when planning a strategy to ensure forage stocks for dairy farms. In regions with high summer temperatures, choosing early maturity maize hybrids or delaying planting date should be considered to avoid high temperature stress during silking and kernel development. As regard to harvesting management, monitoring daily temperatures might help to better decide whether harvesting and chopping should be anticipated when drought occurs. High temperatures around pollination might be considered as an indicator that silage yield or quality would not increase or improve substantially after a relieving rain. Finally, planting alternative forages, such as Sorghum species, should also be considered to minimize the risk associated to growing maize in regions with high summer temperatures (Aydin et al, 1999; Amer et al, 2011). Sorghum species are characterized for having greater resistance to drought stress than maize. Compared to maize, Sorghum species usually require a delayed planting date, therefore escaping to high summer temperatures during kernel development.

Implications

Dry matter yield and composition of maize whole-plant for silage can be controlled by multiple management factors. Despite this, uncontrollable environmental factors, such as drought stress and heat stress, can have major effects on DM yield and composition of maize whole-plant for silage. Results from this study show that low DM yields and poor quality of maize whole-plant for silage are beyond drought stress. Daily maximum temperatures should be considered when planning strategies to insure good quality forage supply and reduce risk in dairy farming systems.

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Table 4 - Dry matter yield, DM concentration and grain component of maize hybrids tested at four sites in Georgia during 2012 (data from Coy et al, 2012).

	Site				SEM	P <	
	Blairsville	Calhoun	Griffin	Tifton		Hybrid	Site
DM Yield, kg ha^{-1}	26,601	24,416	23,802	33,757	2,492	0.04	0.01
DM Concentration, %	37.7	48.8	49.9	48.6	3.2	0.07	0.01
Grain Component, %	47.5	35.9	50.0	49.3	3.6	0.01	0.01

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