Chapter 2

Environmental Factors Affecting Corn Quality for Silage Production

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Additional information is available at the end of the chapter

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Abstract

Corn silage is a major ingredient of diets for dairy cattle. Environmental factors can affect the yield and composition of corn silage. Drought and heat are two common environmental factors that affect silage yield and quality. Corn silages with low concentrations of dry matter, high concentrations of protein, high concentrations of fiber, and low concentrations of starch indicate that the crop was harvested too early, that abiotic stresses affected the structure of the plant, or a combination of both. Drought stress during vegetative stages does not affect yield and nutritional composition as much as during reproductive stages. High environmental temperatures (>35 °C) can also induce kernel abortion. The effects of abiotic stresses on cell wall composition are less clear. Drought stress would likely increase fiber digestibility, whereas heat stress would decrease fiber digestibility. These statements are somehow contradictory in the sense that drought stress and heat stress likely occur simultaneously. Management practices, such as hybrid selection and planting date, should be considered to avoid silking and early kernel development during season of very high environmental temperatures.

Keywords: corn silage, drought stress, heat stress, abiotic stress, nutritional quality

1. Introduction

Whole-plant corn silage is a major ingredient of diets fed to dairy cattle; therefore, producing high-yielding and good-quality corn silage is critical for minimizing production costs in dairy farming systems. The US dairy industry is composed of 9.2 million cows and approximately 4.5 million replacement heifers [1], which consume approximately 60 million (metric) tons of corn silage per year (**Table 1**). The high inclusion of corn silage in diets for dairy cows is attributed to multiple factors. First, corn silage is an attractive feed source because of high yield potential.

For example, dry matter (DM) yields per acre are substantially greater for corn silage than for alfalfa hay (12,600 and 7200 kg/ha, respectively) [2]. Second, corn silage is also characterized by having high concentrations of energy. Under normal climatic conditions, the corn plant contains a great proportion of starch-containing grains. This starch is highly digestible and therefore is an important source of energy for cattle. Finally, corn silage also provides fiber in ruminant diets. Dairy cows require a minimum amount of dietary fiber to ensure ruminal and whole-animal health [3].

Different crop management practices, such as planting density, nitrogen fertilization rates, harvesting time, or harvesting height, can affect corn silage yield, corn silage quality, or both [4]. One way or another, most of these factors, if not all, can be controlled based on managerial decisions. In addition to controllable factors, there are several uncontrollable environmental factors that can substantially affect the dry matter yield and the nutritional composition of corn used for whole-plant corn silage.

	Milk cows	**Replacement**	**Total**
Cow inventory, million heads	9.2	4.5	–
Corn silage consumption, kg/head/day	15.0	5.5	–
Corn silage consumption, million ton[1]/year	50.4	9.0	59.4
Corn silage price, $/ton[1]	45	45	45
Expenditure in corn silage, billion $/year	2.26	0.41	2.67

[1]Metric ton = 1,000 kg

Table 1. Consumption and expenditure for corn silage by the US dairy industry.

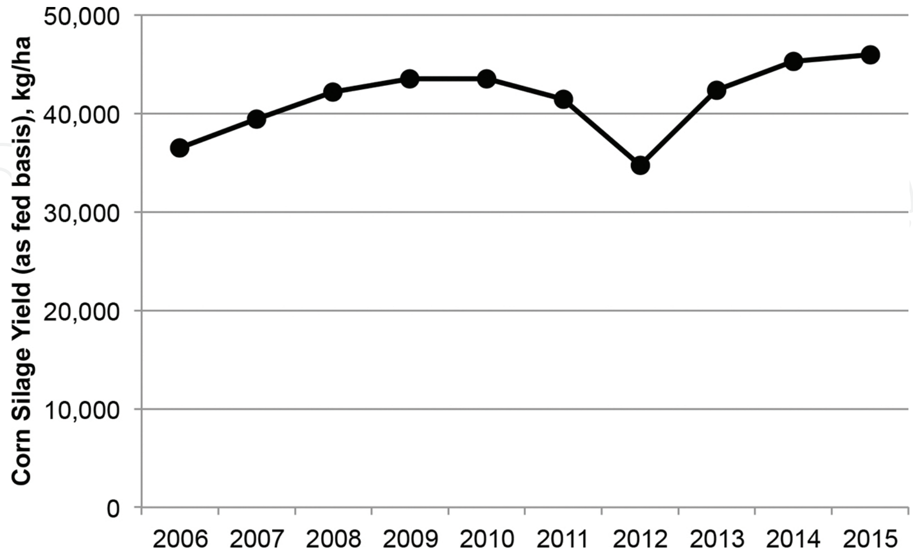

Figure 1. National US corn silage yields (kg/ha, as-fed basis). Spring and summer drought of 2012 will be remembered as one of the "worst agricultural calamities in the United States" [21].

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Drought and heat stresses, also known as abiotic stresses, are two common and interrelated environmental factors that frequently affect corn silage yield and quality [4]. The impact of these factors can be substantial. For example, the drought of 2012 reduced US national silage yields by 16.3 % when compared to 2011 (**Figure 1**). This reduction in yield caused the United States an economic loss between $700 and $800 million for 2012. This loss does not take into account the overall impact to the dairy industry, such as increases in feed prices for hay and corn grain.

Even though drought stress and heat stress are uncontrollable factors that affect corn silage yield and quality, certain management practices can be utilized to attenuate their potential negative impact. The objective of this chapter is to describe such practices so that crop managers can minimize the negative effects of abiotic stresses in yield and quality of corn silage.

2. The corn plant

The corn plant is characterized by having a single erect stem that is divided into basic units known as phytomers. Each phytomer consists of a leaf blade, a leaf sheath, a node, an internode, and the axillary bud. Different from most other grasses, the corn plant has two separate inflorescences per plant, the tassel and the ear, which are the male and the female inflorescences, respectively. The husks are leaves that cover the ear, where corn kernels develop after pollination. Corn kernels are arranged and inserted in lines on an inner cylinder called the cob, which is originated from the axillary bud from the phytomers.

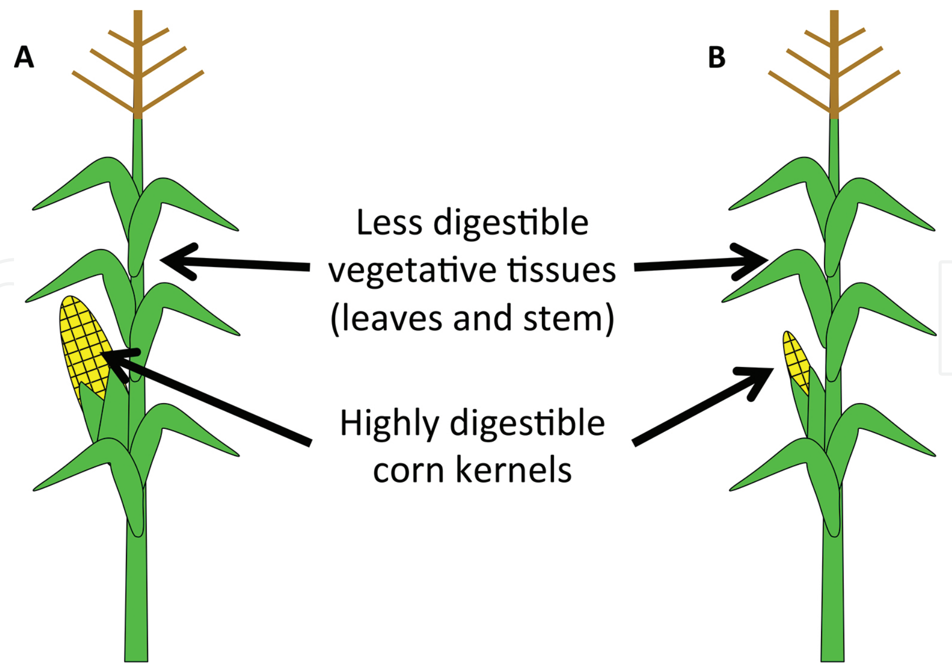

Figure 2. The proportion of grain in the corn plant has a major impact on corn silage yield and nutritional quality. The bigger ear in plant A will result in greater yields of dry matter and greater energy concentration than in plant B.

The structure of the corn plant has a major impact on the chemical composition of corn silage. Carbohydrates synthesized in leaves are mobilized to the grain and stored as starch. Corn kernels comprise 30–52 % of the total plant biomass [5], whereas starch constitutes 70–75 % of the kernel dry weight [6]. Because of the different composition of the grain and the vegetative portion of the plant (high and low concentrations of nonstructural carbohydrates, respectively), the proportion of grain in the corn plant has a substantial impact on the nutritional quality of corn silage (**Figure 2**).

In corn, inflorescence development occurs during the vegetative growth stages of the crop, typically when corn plants have six fully exposed leaves (stage known as V6) [7]. At this stage, the axillary meristem of leaves differentiates into ears [8]. These ears typically produce rows of paired spikelets (**Figure 3**) that produce one ovule-containing floret each. After pollination, when the ovule is successfully fertilized, each floret results in a single corn kernel.

The number of kernels per plant is known as the sink capacity of the plant, which is determined by three components: (1) the number of spikelet rows within the ear, (2) the number of spikelets per row, and (3) the proportion of single and double spikelets within a row (**Figure 3**). Because the sink capacity determines the potential number of kernels in the plant and because the proportion of kernels is a major determinant of the nutritional quality of the whole plant, it is likely that ear differentiation has a major impact on corn silage quality.

Unlike most other grasses, the male inflorescence is separated spatially from the female inflorescence in corn. Every ovule within the ear has to be pollinated to become a developed kernel. For this process, functional stigmas, known as silks, connect the ovules to the exterior of the ear to ensure pollination. The appearance and exposure of the silk to the environment is known as the silking stage and is considered the beginning of the reproductive stage of the corn crop. The first step in the pollination process occurs when pollen grains released from the tassel during anthesis attach to ear silks. The synchrony between anthesis and the emergence of silks (commonly known as anthesis-silking interval, ASI) is critical for adequate kernel pollination and development [9].

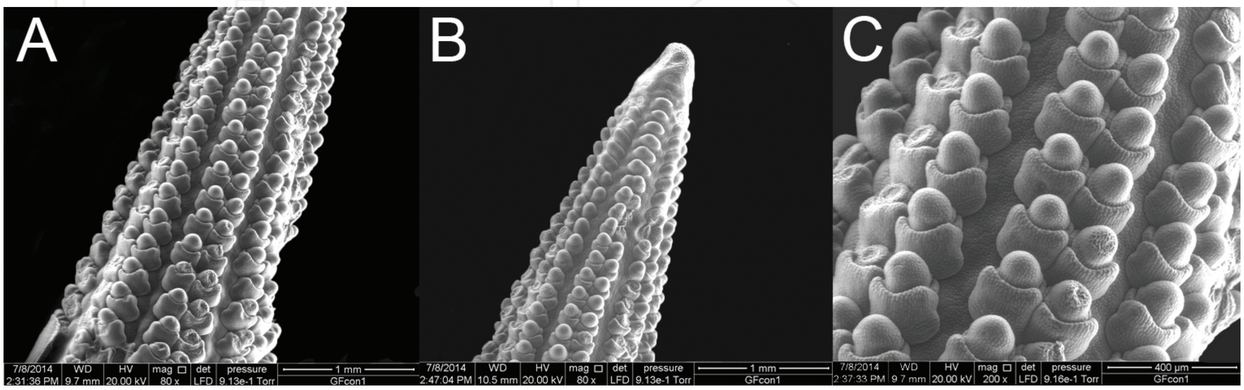

Figure 3. Scanning electron microscopy (SEM) images of corn ears during kernel differentiation. Ear differentiation in the corn plant determines the number of kernels in the whole plant. Normal plants develop row of paired spikelets (A and C), which result in corn kernels. When ear differentiation is affected, irregular rows of single spikelets (B) could be observed. Images were obtained at the Nanoscale Characterization and Fabrication Laboratory (Virginia Tech).

An understanding of corn plant composition is crucial to comprehend the effects of abiotic stresses on the composition of corn silage. In the end, kernel differentiation and kernel development and growth will determine the final number of kernels per plant and, therefore, the starch and fiber concentrations in whole-plant corn silage.

3. Nutritional quality of stressed corn silage

As an ingredient in rations for dairy cows, the value of corn silage relies mainly on its energy concentration and not so much on its crude protein concentration. For example, corn silage typically contains low concentrations of crude protein compared to alfalfa haylage (less than 10 % and more than 15 %, respectively). The low crude protein concentration of the whole corn plant is related to the structure of the corn plant. Corn grain is characterized as having low concentrations of protein [3, 6] due to the high proportion (more than 82 %) of a starchy and nonprotein endosperm. Corn kernels also contain less moisture than vegetative tissues, such as stems and leaves. Therefore, corn silages with high proportions of grain (i.e., a high harvest index) would likely have high concentrations of dry matter (>30 % dry matter), low concentrations of crude protein (<10 % crude protein), low concentrations of fiber (<45 % neutral detergent fiber), and high concentrations of starch (>30 % starch). In contrast, corn silages with relatively low concentrations of dry matter, high concentrations of crude protein, high concentrations of fiber, and low concentrations of starch reflect an indication that either the crop was harvested too early, abiotic stresses affected the structure of the corn plants, or a combination of both.

In a retrospective study performed at Virginia Tech [4], corn hybrids harvested for silage in 2 years, which included 2012, at two sites were analyzed to understand how dry matter yields and nutritional composition were affected by abiotic stresses (**Table 2**). Dry matter yields varied significantly across site-years, but not between hybrids. Even though in 2012 rainfalls were scarce and similar at both sites (262 and 227 mm for the Shenandoah Valley and Southern Piedmont, respectively), dry matter yields and nutritional composition of corn plants differed substantially among locations. Dry matter concentration was substantially low (25.3 % dry matter) in the Southern Piedmont only, likely due to a reduced proportion of the grain component in the whole plant. The low dry matter concentration was followed by a relatively high concentration of crude protein (10.9 % crude protein) and a relatively high concentration of fiber (56.6 % neutral detergent fiber). In contrast to this, dry matter (32.6–37.0 % dry matter) and crude protein (7.1–8.7 % crude protein) concentrations were within typical values for other site-years. Even though the concentrations of fiber were more variable (43.0–52.8 % neutral detergent fiber) in other site-years, these values were lower than those observed in 2012 in the Southern Piedmont. In summary, during the spring and summer drought of 2012, an evident stress was noticed by visual appraisal of corn plots in the Southern Piedmont. This stress manifested with low concentrations of dry matter and high concentrations of crude protein and fiber.

	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
Rainfalls, mm	501	228	280	262
Rainfall Shannon diversity index	0.65	0.66	0.60	0.67
Dry matter yield, kg/ha	12,482	4,556	15,092	12,678
Dry matter concentration, %	37.0	25.3	32.6	35.4
Crude protein concentration, %	8.7	10.9	7.7	7.1
Neutral detergent fiber concentration, %	51.5	56.5	52.8	43.0

Data from Ferreira et al. [4]

Table 2. Dry matter yield and nutritional composition of corn hybrids tested at two locations in Virginia (United States) during 2011 and 2012.

4. Drought stress and kernel development

Water status of the plant is determined by several factors, including the amount and distribution of rainfalls, evapotranspiration, and the water-holding capacity of the soil. The interaction between these factors can substantially affect yields and nutritional composition of corn for silage. Adequate soil moisture is critical to ensure germination and emergence of corn seedlings soon after planting. After seedling emergence, the relatively low evapotranspiration allows plants to grow with minimum stress as long as water content in the soil is adequate. For example, limiting irrigation in corn plots during vegetative stages (i.e., six-leaf stage) reduced neither the grain yield per hectare nor the number of kernels per ear when compared to corn plots receiving complementary irrigation during the vegetative stage [10]. In contrast, limiting irrigation around silking reduced the grain yield per hectare and the weight of the kernels, although the number of kernels per ear was not affected when compared to corn plots receiving complementary irrigation during vegetative stages [10]. These data suggest that when drought stress occurs at vegetative stages, dry matter yields can be compromised but kernel development and the potential nutritional composition of the silage are not necessarily affected.

Unlike in vegetative stages, drought stress during reproductive stages can substantially affect kernel development [9–11]. NeSmith and Ritchie [11] and Çakir [10] reported substantial reductions in the number of kernels per ear when corn plants were subjected to water deficits around silking stage. Although it is clear that drought stress around silking impacts kernel development, multiple mechanisms affect this process.

The seed set is determined during vegetative stages, so the number of ovaries per ear (i.e., the potential number of kernels per ear) is not greatly affected by drought stress around silking

[9]. On the other hand, ovary atrophy or abortion occurs when water stress occurs around silking, reducing kernel development and growth within the ear. Drought stress around silking retards growth and emergence of silks, especially those from apical ovaries (**Figure 4**). The delayed emergence of silks relative to anthesis increases the asynchrony between pollen shed and silking, which can potentially decrease pollination and ovule fertilization. Depending on genotypes and stress levels, drought stress can increase the anthesis-silking interval from 1.9 to 4.8 days [9]. The synchrony between anthesis and silking has become quite relevant in breeding programs, as reducing the time elapsed between anthesis and silking is the main strategy for increasing the tolerance of corn to drought stress [9, 12].

Figure 4. Drought-stressed corn crop showing poor kernel development in the apical region of the ear.

5. Heat stress and kernel development

Drought stress and heat stress tend to occur simultaneously. In general terms, high environmental temperatures will increase evapotranspiration, exacerbating the effects of drought stress, especially when it is accompanied by low relative humidity. Despite this, these two abiotic stresses may affect kernel development by different mechanisms, affecting the composition of corn silage in different ways [4].

Schoper et al. [13] evaluated the effect of drought stress and heat stress on seed set or kernel development while considering the impact of heat stress over the pollen source (i.e., the tassel). As in other studies, the number of kernels per ear decreased approximately 17–19 % when the silk source was subjected to water stress, and the magnitude of this decrease was similar when the pollen source was also subjected to water stress. This last observation indicated that the production of viable pollen was not affected by drought stress. However, when pollen source was subjected to heat stress, the number kernels per ear decreased by approximately 72 % when the silk source was well watered and by approximately 85 % when the silk source was subjected to drought stress. These observations indicated that heat stress had an adverse effect on the development of viable pollen [13], resulting in limited pollination and ovule fecundation.

In addition to limiting pollination, heat stress can limit kernel development after ovule fecundation [14, 15]. Kernel development is divided by a lag phase with little kernel growth and a linear growing phase with major accumulation of dry matter. The lag phase, which starts immediately after pollination and lasts 10 to 12 days after pollination, is critical for kernel development [15]. The endosperm is the structure of the corn 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 [15].

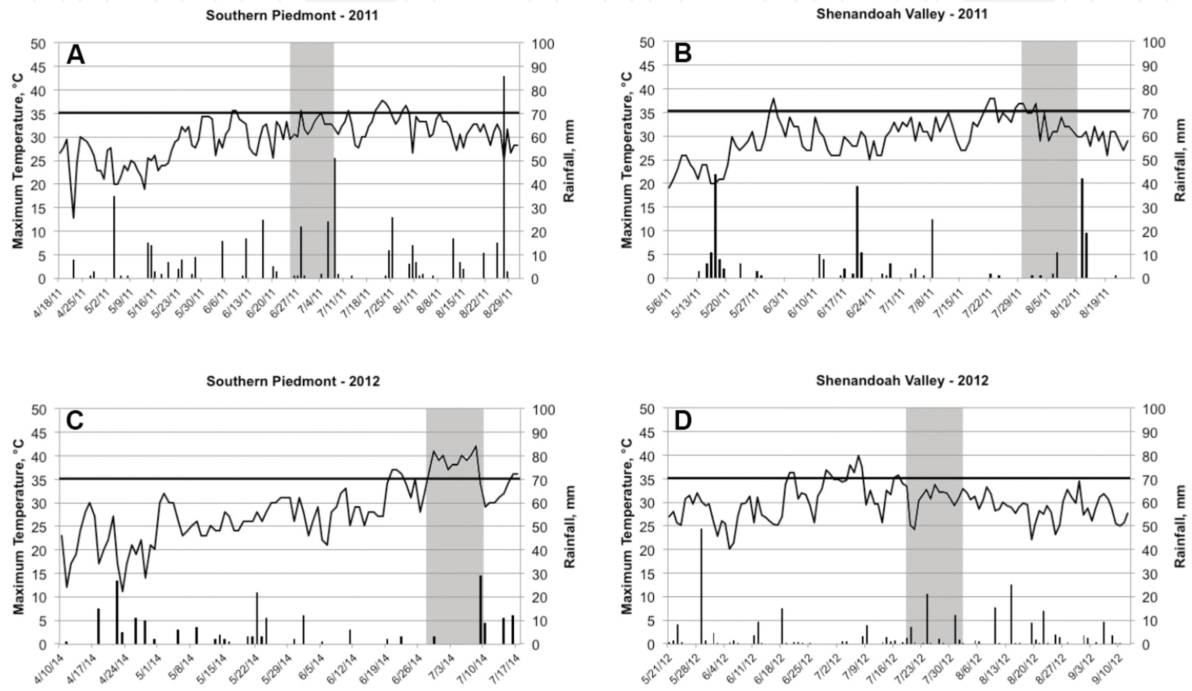

Figure 5. Daily maximum temperatures (line) and rainfalls (columns) during the crop cycle at two regions during 2011 and 2012 in the state of Virginia. The shaded region represents the critical stage for kernel development. The thick horizontal line represents the threshold temperature for heat stress (>35 °C). Prolonged heat stress after silking occurred only in the Southern Piedmont region during 2012 (C), but not in other site-years (A, B, and D). Data from Ferreira et al. [4].

High temperatures immediately after silking limit starch accumulation within the kernels and increase the rate of kernel abortion as well. Cheikh and Jones [15] cultured corn kernels in vitro at different temperatures and observed that heat-stressed kernels (i.e., kernels cultured at 35 °C) accumulated 18–75 % less DM than non-stressed kernels (i.e., kernels cultured at 25 °C). Reduced dry matter accumulation can be related to reductions in starch synthesis within the endosperm when kernels are subjected to temperatures greater than 35 °C [14]. In addition to reduced kernel growth, Cheikh and Jones [15] reported 23–97 % kernel abortion when subjected to heat stress.

In their retrospective study, Ferreira et al. [4] observed that in 2011, maximum temperatures were below 35 °C throughout the whole critical period of kernel development for the Southern Piedmont region, whereas in the Shenandoah Valley region, maximum temperatures were above 35 °C for only a few days during the critical period of kernel development (**Figure 5B**).

Based on these observations, heat stress would not have affected kernel development. In 2012, however, the Southern Piedmont region had maximum daily temperatures above 35 °C for an extended period (11 days) right after silking (**Figure 5C**), whereas maximum daily temperatures were 7.1 ± 2.3 °C lower in the Shenandoah Valley region around silking (**Figure 5D**). 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 during 2012. Therefore, in the Southern Piedmont region, heat stress exacerbated the effects of drought, substantially reducing dry matter yields and kernel development. Similar observations were reported for the southern region of the United States for 2012 [4].

In conclusion, in regions with extended periods of temperatures greater than 35 °C, choosing early maturity corn hybrids or delaying planting date should be considered to avoid drought and heat stress during silking and kernel development.

6. Abiotic stresses and cell wall composition

The effects of abiotic stresses on cell wall composition are less clear than their effects on kernel development. In general terms, and from a nutritional perspective, drought stress would likely increase fiber digestibility (**Table 3**, data Argentina), whereas heat stress would decrease fiber digestibility [16]. These statements are somehow conflicting in the sense that drought stress and heat stress likely occur simultaneously.

	2008	2009
Dry matter concentration, %	32.2	28.5
Crude protein concentration, %	8.1	7.3
Neutral detergent fiber concentration, %	45.0	49.2
Starch concentration, %	18.8	7.0
Fiber digestibility[1], %	44.4	52.6

[1]30 h neutral detergent fiber digestibility

Table 3. Nutritional composition and digestibility of corn silages in Buenos Aires (Argentina) during normal (2008) and drought (2009) years.

Drought stress during early vegetative stages can result in shorter internode lengths as a consequence of limited cell growth or elongation (**Figure 6**). As internodes contain highly lignified tissues (e.g., lignified vascular bundles), the concentration of lignin within the cell wall could be reduced when considering the whole corn plant. In addition to changes in whole plant structure (i.e., internode elongation), lignification might decrease at the tissue level when corn plants are subjected to drought stress [17, 18]. Vincent et al. [17] reported that lignin accumulation in the apical zone of corn leaves was reduced in response to drought stress. Alvarez et al. [18] reported higher concentrations of lignin precursors (i.e., p-coumaric and

Figure 6. Drought-stressed corn crop passed tassel emergence, showing reduced elongation of internodes.

caffeic acids) in xylem sap of drought-stressed corn compared to well-watered corn, suggesting reductions in lignin concentration under drought stress.

7. Abiotic stresses and silage fermentation

Because controlled experiments evaluating the effects of abiotic stresses on corn silage are scarce, most of the knowledge on silage fermentation may be obtained from field experience. One reason for the lack of controlled studies may be that accomplishing and reproducing stress treatments are difficult [19].

One major concern when ensiling stressed corn can be the low DM concentration of the forage. As described before, if poor kernel development occurs, then low DM concentrations will likely occur [4], and therefore it might be very difficult to obtain a high enough DM concentration (>30 % DM) for an adequate ensiling process. In these scenarios, the likelihood of seepage losses or clostridial fermentations may increase [20]. On the other hand, drought stress conditions might also increase solute concentrations, which could decrease water activity and growth of lactic acid bacteria [20]. In regard to silage density, packing may be more challenging with heat-stressed corn as the dried and brittle leaves, combined with the lower content of grain,

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might increase porosity of the silage. Under these scenarios, the use of inoculants to enhance fermentation is highly advised.

8. Conclusions

Abiotic stresses such as drought and heat stress can substantially affect corn silage yield and quality, although the mechanisms by which they act are different. Depending on the moment at which occurs, drought stress can have varying impacts. If drought stress occurs only at vegetative stages, dry matter yields can be compromised but not necessarily its nutritional composition. Alternatively, if drought stress occurs during reproductive stages (i.e., silking), both dry matter yield and nutritional composition can be affected. Heat stress, defined as temperatures above 35 °C, during the initial stages of kernel development can have a major negative impact in both corn silage yields and nutritional composition. Management practices, such as hybrid selection and planting date, should be considered to avoid silking and early kernel development during season of very high environmental temperatures.

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