Silage review: Unique challenges of silages made in hot and cold regions[1]

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ABSTRACT

Silage making can be conveniently divided into field, ensiling, storage, and feed-out phases. In all of these stages, controllable and uncontrollable components can affect silage quality. For instance, silages produced in hot or cold regions are strongly influenced by uncontrollable climate-related factors. In hot regions, crops for silage are influenced by (1) high temperatures negatively affecting corn yield (whole-crop and grain) and nutritive value, (2) butyric and alcoholic fermentations in warm-season grasses (*Panicum*, *Brachiaria*, and *Pennisetum* genera) and sugarcane, respectively, and (3) accelerated aerobic deterioration of silages. Ensiling expertise and economic factors that limit mechanization also impair silage production and utilization in hot environments. In cold regions, a short and cool growing season often limits the use of crops sensitive to cool temperature, such as corn. The fermentation triggered by epiphytic and inoculated microorganisms can also be functionally impaired at lower temperature. Although the use of silage inoculants has increased in Northern Europe, acid-based additives are still a good option in difficult weather conditions to ensure good fermentation quality, nutritive value, and high intake potential of silages. Acid-based additives have enhanced the quality of round bale silage, which has become a common method of forage preservation in Northern Europe. Although all abiotic factors can affect silage quality,

the ambient temperature is a factor that influences all stages of silage making from production in the field to utilization at the feed bunk. This review identifies challenges and obstacles to producing silages under hot and cold conditions and discusses strategies for addressing these challenges.

Key words: silage problem, silage production, temperate crop, tropical crop

INTRODUCTION

Silage making is an old agricultural practice that started more than 3,000 yr ago (Wilkinson et al., 2003). However, a rapid increase in the application of this technology occurred after the 1940s as a result of the mechanization of forage harvesting (Wilkinson et al., 2003). Silage making is well established in the temperate regions of North America and Europe but has only recently become popular and widespread in tropical regions (Wilkins and Wilkinson, 2015).

Production of high-quality silage is dependent on both controllable and uncontrollable factors. Silage management factors that are under the control of the farmer are forage species and agricultural background, stage of maturity or moisture concentration at harvest, harvesting and ensiling methods, type of storage structure, use of silage additives, feed-out methods, feed bunk management, and diet formulation (Mahanna and Chase, 2003). Uncontrollable climate-related factors that are common or specific to warm or cold regions can adversely affect silage production and utilization and can influence some of the factors listed above, such as moisture concentration at harvest. The objective of this article is to identify challenges and obstacles to producing silages under hot and cold conditions and to discuss strategies for addressing these challenges.

SILAGE MAKING IN HOT AREAS

Effects of High Temperature on the Yield and Attributes of Crops and Silages

The concentration and digestibility of NDF are by far the most important variables related to forage nutritive value. However, in ensiled forages, the nutritive value is further affected by the fermentation pattern (extent and profile), which in turn can influence DMI (Huhtanen et al., 2007). The prevailing climate can exert considerable effects on the DM yield and quality of silages, and in some instances these effects may surpass the effect of maturity at harvest on the ensiling process.

Corn and Sorghum. Relatively few studies have focused on the effects of temperature on the yield of whole corn plants. For instance, Struik (1983) reported that high temperatures accelerated kernel development and leaf senescence, reducing kernel viability and final plant yield. Effects of temperature alone on crop yields are typically determined via modeling to avoid the confounding effects of several other factors such as the location, soil type, nutrient status, management, and other climatic attributes. Most of the existing research has focused on corn kernel yields rather than yields of the whole plant. Muchow et al. (1990) used modeling to demonstrate the inverse relationship between increasing temperatures and corn grain yield in the following cities: Gainesville, Florida; Katherine, Australia; Quincy, Florida; Champaign, Illinois; and Grand Junction, Colorado. They highlighted the importance of the length of the grain-filling period in determining the yield because the DM in the grain is largely accumulated after flowering and is typically inversely related to increasing temperature. Schlenker and Roberts (2006) reported that corn yields decreased in a nonlinear manner with temperatures above 25°C, but even short periods above 30°C caused considerable yield losses. Likewise, based on climate and yield data spanning most US counties from 1950 to 2005, Schlenker and Roberts (2009) reported that the yield of corn grain gradually increased up to 29°C, but temperatures above this threshold markedly reduced yields. They noted that the slope of the decline above the optimum value of 29°C is much steeper than the incline below it. In addition, Bassu et al. (2014) evaluated 23 models for corn growth at 4 locations representing a wide range of corn production conditions around the world (Ames, Iowa; Lusignan, France; Morogoro, Tanzania; and Verde, Brazil). Several models indicated that temperature increases above 30°C reduced grain yield by 0.5 t/ha per Celsius degree.

Corn silage is the most energy dense forage source used in dairy cow diets in tropical environments (Bernardes and Rêgo, 2014; De Oliveira et al., 2017). How-ever, corn silage from hot or tropical regions is usually poorer in quality compared with corn silage produced in cool or temperate climates. Adesogan (2010) reviewed the chemical composition of 3,070 corn silage samples from Florida and New York analyzed at the Dairy One Forage Laboratory (Ithaca, NY) over a 5-yr period (2004–2009). Florida corn silages consistently had lower concentrations of starch and greater concentrations of acid detergent-insoluble CP (**ADICP**), NDF, ADF, and lignin. The greater cell wall and ADICP concentrations in the Florida silages may be attributable to the effects of higher temperatures on cell wall deposition, although this cannot be verified because the data were not from a controlled experiment. Nevertheless, several authors have reported that high temperatures increase fiber or lignin deposition (Wilson et al., 1991; Moore and Jung, 2001). This is partly because higher temperatures increase the rate of plant development (Buxton, 1996) and the activity of lignin synthetic enzymes (Buxton and Fales, 1994). These responses increase the partitioning of DM to more lignified tissues, such as the shoots (Hardacre and Turnbull, 1986; Cone and Engels, 1990; Moore and Jung, 2001). The higher ADICP concentration in the Florida versus New York silages sampled by Adesogan (2010) is consistent with the effects of higher temperatures in the study of Garcia et al. (1989). Likewise, Kim and Adesogan (2006) reported that a higher ensiling temperature (40 vs. 20°C) increased the concentration of ADICP or heat-damaged proteins in corn silage. Reactions between sugars and amino groups form the ADICP through the Maillard reaction, which occurs at >40°C in silages (Muck et al., 2003). The rate of the reaction also increases exponentially with temperature (Goering et al., 1973). Heat-damaged proteins formed in the Maillard reaction are usually indigestible in vivo; therefore, elevated temperatures can reduce the feed value of protein in corn silage.

Logically, lower grain yields at higher temperatures also result in lower starch concentration in corn silage due to the influence of temperature on starch synthase, the enzyme controlling starch synthesis in the grain. Keeling et al. (1994) reported that temperatures above 30°C irreversibly inactivate starch synthase, precluding the deposition of starch in the kernel. However, a study conducted in Brazil found that corn silage produced on intensive dairy farms located in the south and southeast had satisfactory starch concentration (De Oliveira et al., 2017), as shown in Figure 1.

Corn silage digestibility is usually decreased at high temperatures due to the reduction in starch concentration and increase in lignin and fiber deposition in the plant. Cone and Engels (1990) reported that corn grown at higher temperatures (12 h at 30°C and 12 h

at 24°C) exhibited decreased cell wall thickness, cell diameter, and cell wall yield but had double the lignin content, resulting in a decrease in in vitro digestibility compared with corn grown at low temperature (12 h at 18°C and 12 h at 12°C). Crasta and Cox (1996) also reported that growing corn at a warmer location reduced in vitro DM digestibility relative to growing it at a cool location. Adesogan (2010) reported that Florida corn silages consistently had lower total digestible nutrient concentrations compared with New York corn silages, but NDF digestibility (**NDFD**) values did not consistently differ.

Corn hybrids grown in Brazil predominantly have flint kernels and the associated greater proportion of vitreous endosperm. Although kernel processing improves starch availability (Ferraretto and Shaver, 2012), many farmers in tropical regions do not have access to kernel processors. For instance, in Brazil farmers use pull-type harvesters without kernel processors (Bernardes and Rêgo, 2014). When corn is ensiled, the rate of starch digestion increases as the length of storage time increases (Macken et al., 2003; Benton et al., 2005; Carvalho et al., 2017). Because of this, several beef and dairy farmers in Brazil have adopted high-moisture corn silage, reconstituted corn grain silage (Carvalho et al., 2017), and ear corn silage (snaplage) as feed sources. Fernandes (2014) ensiled flint and dent corn grains harvested at different maturities. Although vitreousness and maturity affected starch digestibility before ensiling, no differences were observed in starch digestibility after 60 d of storage. In fact, Correa et al. (2003) did not observe any differences in starch digestibility, DMI, or milk yield in dairy cows fed diets containing flint versus dent corn silages. Thus, vitreousness of grain remains important for selection of grain types to be rolled and ground and fed as dry corn grain, but not for silages (Owens, 2008). Considering that both starch and NDF are the major nutrients in corn silage and that starch digestibility typically increases during ensiling (Daniel et al., 2015), NDFD is the principal nutritional trait used for selecting corn hybrids for silage production (Lopes et al., 2009; Zopollato and Sarturi, 2009; De Oliveira et al., 2017).

Higher ensiling temperatures typically lead to a shift from a homolactic to a heterolactic microbial population. Zhou et al. (2016) examined the influence of ensiling temperature (5, 10, 15, 20, and 25°C) on fermentation characteristics and microbial counts of corn silage. A 10-fold increase in lactic acid bacteria (**LAB**) counts was detected after 28 d of ensiling at 25 versus 5°C. Furthermore, at the higher ensiling temperatures (15–25°C), shifts from homolactic to heterolactic bacteria occurred, whereas the homolactic bacterium *Lactobacillus sakei* dominated the fermentation at 5 and 10°C. Due to such shifts in the microbial population, corn silages produced in warm climates or at higher temperatures typically exhibit a more heterolactic fermentation as evidenced by greater acetate concentrations and lower lactate concentrations (Kim and Adesogan, 2006; Adesogan, 2010; Wang and Nishino, 2013; Weiss et al., 2016). Zhou et al. (2016) reported that silages incubated at higher temperatures (15–25°C) had higher levels of acetic acid and a higher acidification rate than those incubated at lower temperatures (5 and 10°C). In addition, ensiling at the 2 highest temperatures (20 and 25°C) eliminated the lag time before the pH declined, whereas lag times for the lower ensiling temperatures were 2 to 3 d.

Heterolactic fermentations often lead to higher DM losses during ensiling (McDonald et al., 1991) but are usually associated with improved aerobic stability

(A)

(B)
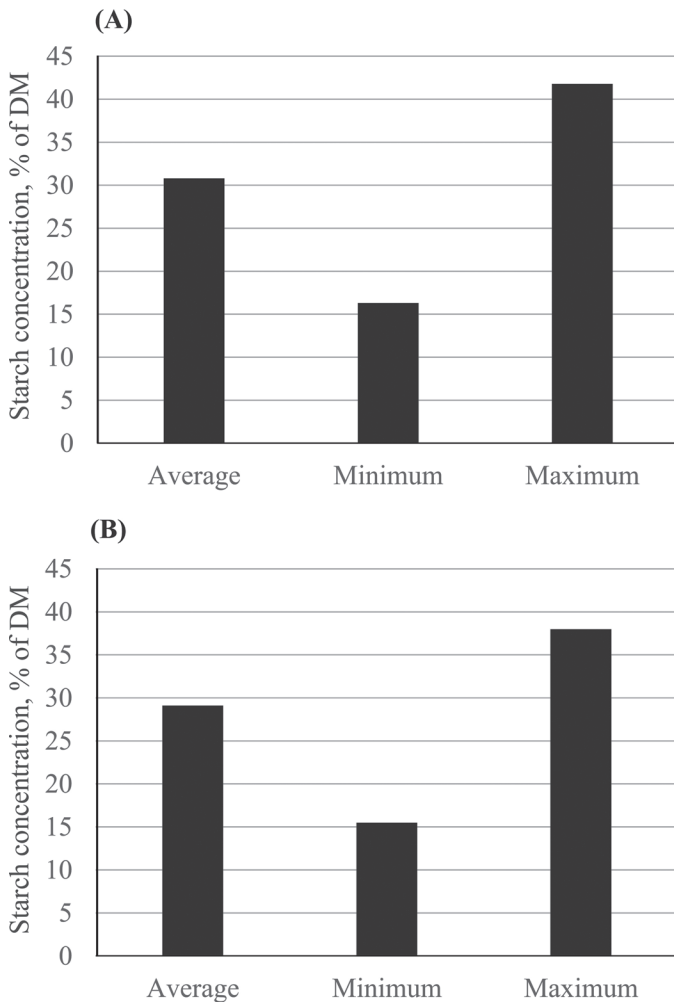
Figure 1. Starch concentrations of tropical corn silages from the central core (A) and the top (B) of the silos. Data from De Oliveira et al. (2017).

(Driehuis et al., 1999) because of greater concentrations of antifungal compounds such as acetate. Nonetheless, under hot or tropical conditions, silages are more prone to aerobic spoilage (Ashbell et al., 2002; Adesogan, 2009) and may still benefit from additives that improve aerobic stability, such as weak acids (e.g., benzoate and sorbate; Da Silva et al., 2014; Bernardes et al., 2015) and heterolactic inoculants (e.g., *Lactobacillus buchneri*; Queiroz et al., 2013). This is because high temperatures are often more conducive for the growth of spoilage organisms, and the levels of naturally produced antifungal fermentation products are often insufficient to curtail their growth. For example, Koc et al. (2009) examined the aerobic stability of silages at room temperature (20°C) or elevated temperatures (30–37°C). The highest yeast and mold counts and CO_2 production occurred at the higher temperatures. Likewise, when corn and wheat silages were exposed to air at 10, 20, 30, and 40°C, the highest yeast and mold counts and greatest deterioration occurred at 30°C (Ashbell et al., 2002). However, Weinberg et al. (2001) reported that aerobic stability of corn and wheat silages was greater at a higher (37–41°C) versus a lower (33°C) temperature.

Sorghum is an annual crop that is well adapted to environments with limited rainfall and high temperatures (Mann et al., 1983), but sorghum silage typically has a lower nutritive value than corn silage (Pino and Heinrichs, 2017). In Brazil, seed companies have focused on taller varieties with high DM yield and low grain:forage ratio. Additionally, a higher percentage of grains can pass undigested through the animal with sorghum silage compared with corn silage (Martin and Peel, 2013). Another challenge with sorghum crop is bird damage during grain ripening (Duncan, 1980). Therefore, sorghum has been adopted as an alternative to corn for the second crop or even for the summer crop in areas susceptible to drought. Dual-purpose varieties seem to have a more favorable grain:stover ratio and DM yield and avoid lodging.

Tropical Grasses. Beyond corn and sorghum silages, tropical grass silages are important forages in warm climates. Warm-season grasses often have a higher moisture content at harvest than cereal crops. Therefore, harvest timing is critical, and wilting or application of additives is often needed to reduce the risk of a butyric fermentation and effluent production (Nussio, 2005). Besides the high moisture, the low concentration of water-soluble carbohydrate (**WSC**) can impair the ensiling of some warm-season grasses. Pholsen et al. (2016) found lower LAB numbers and WSC concentration in Guinea grass (*Panicum maximum*) compared with Napier grass (*Pennisetum purpureum*). Guinea grass silages were poorer in quality due to lower DM and lactic acid concentrations and higher pH and ammonia nitrogen concentrations. In addition, the pH of Guinea grass silage failed to decline below 4.0, allowing a clostridial fermentation that resulted in increased butyric acid and ammonia nitrogen production.

Although wilting is a feasible strategy to decrease moisture content in short and thin-stemmed crops, several species of warm-season grasses used for silage are tall and have thick stems (e.g., *Panicum maximum*, *Pennisetum purpureum*) and are consequently difficult to wilt. Therefore, ensiling tropical grasses with absorbents can produce silages with higher intake potential and improved DM digestibility depending on the additive selected (Bernardes et al., 2005). Hence, in small-scale silage production, dry by-products (e.g., soybean hulls, citrus pulp, cassava pulp, wheat bran, rice bran, corn gluten feed), energetic meals (e.g., corn meal, sorghum meal, pearl millet meal), or even protein meals (e.g., cottonseed meal, peanut meal, sunflower meal) have been used as absorbents during the ensiling of tropical grasses (Gusmão et al., 2017). Coffee hulls, rice hulls, and cotton hulls have also been examined, but the low digestibility and the presence of antinutritional factors in these absorbents often produces low-quality silage even with optimal moisture levels (Carvalho et al., 2007).

Sugarcane. Sugarcane is a competitive tropical forage source due to its high DM yield (e.g., 40–50 t of DM/ha) and suitable nutritive value at maturity (Daniel et al., 2017). Although sugarcane is often harvested and fed daily during periods of pasture shortage, it is also ensiled to avoid later lodging, reduce the risk of loss by fire, and avoid the need for daily harvesting (Pedroso et al., 2008). As sugarcane is a semiperennial tropical grass, its field life span may be prolonged by uniform harvesting and postharvest management. However, due to its high content of soluble carbohydrates and large yeast population (Ávila et al., 2010), ensiling sugarcane results in the conversion of part of the soluble sugars into high levels of volatile organic compounds, principally ethanol (Daniel et al., 2013c). For many years, farmers and technicians claimed that ethanol depressed DMI. To date, considerable evidence indicates that ethanol does not impair feed intake (Ham et al., 1994; Randby et al., 1999; Raun and Kristensen, 2011; Daniel et al., 2013a) and actually is a valuable energy source. However, because ethanol is volatilized from the silo face during diet mixing and in the feed bunk (Daniel et al., 2013a), considerable amounts of net energy are lost when sugarcane is conserved by natural fermentation. Although ethanol (7.1 Mcal/kg) has a higher content of gross energy than carbohydrates (4.2 Mcal/kg), replacing dietary carbohydrates with ethanol has led to similar or even lower feed efficiency (Ham et al., 1994; Randby et al., 1999; Daniel et al., 2013a). Hence,

ethanol fermentation is still undesirable. Application of effective additives to sugarcane at ensiling (e.g., sodium benzoate, *L. buchneri*) conserves most soluble carbohydrates, and its nutritive value is comparable with freshly chopped sugarcane (Queiroz et al., 2008).

Sugarcane silage comprises 3 main fractions: soluble carbohydrates (mainly sucrose), fermentation end products, and NDF; crude protein, ether extract, and ash compose less than 7% of sugarcane silage DM. The true digestibility of the soluble fraction (soluble carbohydrates + fermentation end products) is almost 100%; therefore, the nutritive value of sugarcane is primarily a function of the concentration and digestibility of NDF. The concentration of NDF is dependent on crop maturity, genotype, soil fertility, and use of effective silage additives, which ultimately affects the recovery of soluble sugars and, by dilution, the NDF concentration. Compared with temperate grasses, sugarcane NDFD is typically low (<35%; Oliveira et al., 2011) due to the higher proportion of indigestible NDF (~50% of NDF) and lower digestibility of potentially digestible NDF (Daniel et al., 2013b). Compared with other grasses and legumes, sugarcane presents a low content of lignin in NDF. However, the negative effect of lignin on sugarcane fiber digestibility is even more pronounced than in other grasses (Daniel et al., 2017). The low nanoporosity of the sugarcane cell wall, especially for regions with higher lignification, is a major determinant of sugarcane cell wall recalcitrance (Maziero et al., 2013). Additionally, the arrangement of lignified tissues in C4 grass stems, such as the formation of a sclerenchyma ring in the stem cortex zone, further hinders particle breakdown (Wilson, 1993). These properties increase ruminal retention time and physical fill, accounting for the higher physical effectiveness of sugarcane NDF (Goulart et al., 2009; Sá Neto et al., 2014) and the lower DMI of sugarcane-based diets (Correa et al., 2003; Oliveira et al., 2011) compared with temperate forage-based diets (e.g., corn silage).

Two strategies have been used to overcome the low NDFD of sugarcane silage. Chopping sugarcane into fine particles benefits the packing and preservation of silage and decreases the sorting that can result in nutrient imbalances and digestive disturbances. Moreover, sugarcane NDF retains its high physical effectiveness even when it has a short particle length (Campos, 2015). Santos (2010) reported a linear increase in milk yield without alteration in milk fat content in crossbred Holstein–Jersey cows fed sugarcane with an increasingly reduced particle size. Hypothetically, finely chopped particles increased the ruminal turnover and lowered the constraints that rumen fill exerted on feed intake (Gherardi et al., 1992).

Another strategy for improving the nutritive value of sugarcane silage-based rations is to increase the dietary proportion of concentrates (Costa et al., 2005). Sá Neto et al. (2014) demonstrated that formulating dairy rations with an equal physically effective NDF resulted in similar production performance when sugarcane was substituted for corn in the diets of dairy cows. Reported values of the physical effectiveness factor of sugarcane NDF are around 20% higher than those of corn silage NDF (Goulart et al., 2009; Sá Neto et al., 2014).

Considering its high physical effectiveness, sugarcane silage is a very attractive forage source for beef feedlots because a low dietary inclusion is enough to meet physically effective fiber requirements. Additionally, silage moisture assists in bunk management, reducing dust and fines and improving the ration texture compared with dry roughages (e.g., hay). Hence, a very high stocking rate is feasible in feed yards that use sugarcane silage-based diets.

Aerobic Deterioration of Silages—An Important Issue in Hot Climates

Aerobic microorganisms are by far the greatest single source of losses in silage making (Woolford, 1990). The aerobic deterioration of silage causes DM and nutrients losses (McDonald et al., 1991). When offered to ruminants, spoiled silage is often partially or completely refused (Gerlach et al., 2013), and if consumed it can affect metabolic parameters and immunity (Korosteleva et al., 2007). Furthermore, aerobic deterioration of silage can cause problems for humans due to transfer of pathogens and mycotoxins from the silage to other feeds and animal products such as milk (Ogunade et al., 2016).

Aerobic microorganisms initiate their activities in the field and when the silo is being filled; however, the process of aerobic deterioration becomes more pronounced during storage and the feed-out phases (Honig, 1991). Even during storage, tropical environments can have adverse effects on the physical properties of plastic films used to cover silos. In particular, tropical climatic conditions reduce air-tightness and resistance of the film to radiation and high temperatures (Paillat and Gaillard, 2001). Thus, in warm climates, plastic films can readily become more permeable to air, especially if they are used to cover silages for long storage periods.

At the time of unloading, high temperatures can increase the growth rates of spoilage microbes, leading to increased silage deterioration. Ashbell et al. (2002) exposed corn and wheat silages to air for 3 or 6 d at 10, 20, 30, and 40°C. The greatest deterioration occurred at 30°C due to greater growth of yeasts at this

temperature. McDonald et al. (1991) also noted that the temperature range of yeasts is very variable, with growth occurring from 5 to 50°C and optimum growth of most species occurring at 30°C. These authors also noted that the optimal temperature for spoilage molds and clostridia was between 25 and 35°C and 37°C, respectively. Bonner and Fergus (1960) studied the effects of 3 temperatures and 6 relative humidities on the growth and survival of 10 fungi isolated from silage. They discovered that no growth occurred at 50°C, but all fungi grew at 25 and 37°C when the relative humidity exceeded 85%. Fungal growth was optimized at a relative humidity of 100% and 25°C. Therefore, warm, moist climates are more likely to increase the growth of spoilage fungi and accelerate silage deterioration.

Preventing Aerobic Deterioration

Once silage begins to deteriorate due to aerobic exposure, little can be done to curtail the process. Consequently, preventing silage spoilage is key, and efforts toward this goal should be directed before, during, and after ensiling. Management practices that can be used to prevent aerobic spoilage before ensiling include harvesting forages at the correct DM concentration and particle size. These factors are critical to optimize the packing density and minimize silage porosity, factors that predispose silage to spoilage. The ideal DM concentration and particle size are crop specific. Additional management strategies for preventing aerobic deterioration include packing forages into the silo at an ideal rate and density, using silage additives to reduce aerobic spoilage, and choosing the type of plastic cover and daily feed-out rate and method that minimize spoilage. Each of these factors is discussed below with a focus on warm climates.

Packing and Filling. The recommended minimum pack density of silages is 705 kg/m^3 (as-fed basis) with a porosity of less than 0.4 (Holmes, 2009). However, density is usually lower in the top layers than in the center layers of bunker and stack silos (D'Amours and Savoie, 2005). Borreani et al. (2008) reported bulk densities in the peripheral areas (top center and top lateral; 0.50 m from the top) of bunker silos and stacks of corn silage on 62 commercial farms to be in the range of 133 to 487 and 141 to 428 kg/m^3 for bunkers and stacks, respectively. Corresponding bulk densities at the cores of the surveyed silos were 578 and 593 kg/m^3, respectively. The lower values observed in the peripheral areas were found on farms where bunker silos were overfilled, with the silage mass extending above the walls of the silo. Researchers in Brazil also observed that overfilled bunker silos had lower silage densities

and greater yeast counts in the top layers of the bunker (T. F. Bernardes, I. L. De Oliveira, and L. M. Lima, Department of Animal Science, Federal University of Lavras, Brazil; unpublished data). These observations highlight the importance of taking particular care to fill bunker silos in a manner that ensures adequate packing density and oxygen exclusion.

Producers achieving high packing densities use tractors with weights and tire widths that promote a high degree of compaction and pack the silage in shallow (<0.15 m) layers. When the delivery rate to the silo is high (as when harvesting with self-propelled harvesters), one or more additional packing tractors are needed. In a well-packed silo, all tractor tires will pass over the entire packing layer surface at least once, with more passes being beneficial (Muck and Holmes, 2000). Because density near the wall of a bunker silo is frequently lower than that toward the center, packers should make additional passes near the walls.

Silage Additives. In warm climates, cereal silages are even more likely to deteriorate because aerobic yeasts are more active at high temperatures. Several chemical additives can reduce aerobic spoilage; some of the most effective include potassium sorbate and sodium benzoate. A study evaluated 2 potassium sorbate and sodium benzoate application rates in improving the aerobic stability of corn silage (Bernardes et al., 2015). Both additives applied at 2 g/kg effectively reduced silage spoilage compared with untreated corn silage. Because the high cost of the chemical additive can limit its application to the entire silage mass, it may be applied only to the surface of the silage, where the risk of deterioration is greatest (Da Silva et al., 2014).

With respect to microbial inoculants, several studies have shown that inoculants containing *L. buchneri* alone or a combination of *L. buchneri* and homolactic acid bacteria can improve the aerobic stability of silages. For instance, Queiroz et al. (2012) showed that an inoculant containing *L. buchneri* and *Pediococcus pentosaceus* reduced the amount of spoilage in 3.6-m-wide bags by more than 50%. Mari et al. (2009) also showed that application of the same inoculant reduced yeast counts and increased the aerobic stability of corn silages on several commercial farms.

Sealing. A plastic film to cover silage has to fulfill 3 essential functions. The film should prevent precipitation and damage caused by rain, hail, or birds. It should be UV resistant to remain intact after prolonged exposure to sunlight. Finally, it must ensure anaerobic conditions during ensiling (Bernardes, 2016). Besides having a high-quality plastic, the nature of how the film covers the forage is important. Recently, studies were undertaken to examine the use of oxygen barrier film
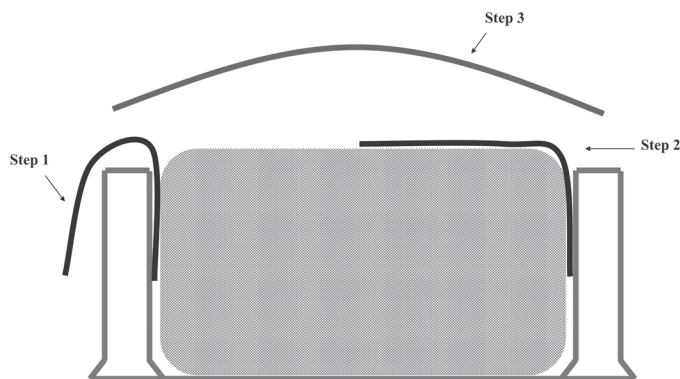
Figure 2. Bunker lining diagram. Step 1: before silo filling, place a plastic sheet along the length of the sidewall with approximately 2 m of excess draped over the wall. Step 2: sidewall plastic should overlap onto the forage top at the end of filling. Step 3: cover the bunker with additional plastic film. © 2016 T. F. Bernardes. Published in Bernardes (2016) under a CC BY 3.0 license. Available from https://doi.org/10.5772/65445.

on the walls and top regions of bunker silos compared with only a single layer of standard polyethylene film on top of the bunker (Lima et al., 2017). With the oxygen barrier film, silage next to the bunker wall exhibited a quality that was similar to that in the central core and superior to that in bunkers that were sealed only with a top film (Borreani and Tabacco, 2014). Lining the inside of bunker walls before filling is an alternative approach to ensuring more complete exclusion of oxygen during ensiling and storage (Bernardes, 2016; Figure 2). Thus, using high-quality plastic film and ensuring close contact of the film with the silage surface are essential for the production of high-quality tropical silages (Lima et al., 2017).

Weighting the Plastic Cover. Borreani and Tabacco (2007) presented the results of a study on different silage sealing systems. A farm bunker silo was covered with a single black-on-white sheet. Half of the width of the sheet was covered with tires (25 kg/m^2), and the other half was covered with gravel (200 kg/m^2). The silo was opened during the summer and had a low feed-out rate (12 cm/d). The results showed that the difference in sealing system affected the temperature in the peripheral areas of the corn silage. The silage covered with tires reached a maximum temperature of more than 40°C, whereas temperatures never exceeded 30°C in silage covered with gravel.

The amount of soil placed on top of the plastic cover also has an effect on silage quality. Bernardes et al. (2009) studied the effectiveness of several sealing strategies on reducing losses in the top layer of tropical silages in Brazil. Covering with a black plastic sheet along with soil (100 kg/m^2) reduced losses and was associated

with decreased pH and ash content and lower counts of yeasts. However, most farmers are very reluctant to cover horizontal silos with soil, particularly if the silo is large, as they do not believe that the labor and costs can be economically justified. Moreover, the soil used as a cover can contaminate the silage during unloading. Thus, alternative covering strategies to reduce aerobic deterioration of the top layer in bunkers filled with corn silage were investigated. Three treatments were evaluated: (1) black film (control), (2) black film plus sugarcane bagasse (10 kg/m^2) over the sheet, and (3) black film plus soil (30 kg/m^2) over the sheet (Amaral et al., 2010). Treatments did not affect the temperatures during the early part of the storage period, but after about 80 d of fermentation the temperature in the control silage was higher than that in other treatments. This can be attributed to increased permeation of oxygen through the film during prolonged storage, as permeation was reduced by the presence of soil or sugarcane bagasse over the sheet.

It is important to emphasize that keeping the plastic cover weighed down is critical during storage and feed-out periods. Honig (1991) reported that during unloading, air can penetrate the peripheral areas of a silo by up to 1 m beyond the feed-out face, especially when the sealing cover is not weighted down or is weighted only with tires. This suggests that with this situation, daily removal rates should be higher than 30 cm/d to avoid extended aerobic spoilage.

Feed-Out Rate. Losses during unloading depend on the density of the silage, the ambient temperature, the aerobic stability of the silage, and feed-out rate, which determines the duration that the silage is exposed to air (Muck et al., 2003). The prevailing temperature during unloading depends on the season and geographical location of the silo. In the Netherlands (latitude 53° N), silo face removal rates of 1 to 1.5 m/wk (winter and summer, respectively) were recommended by Vissers et al. (2007) to avoid extended aerobic spoilage. An average removal rate of 1.1 to 2.1 m/wk from the silo face is a common recommendation in Wisconsin (latitude 44° N; Pitt and Muck, 1993). Under subtropical conditions, such as in Israel (latitude 31° N), recommended bunker silo unloading rates are 1.4 to 2.1 m/wk (winter and summer, respectively). Unfortunately, there is no definitive answer for the correct feed-out rate in tropical regions. Borreani and Tabacco (2012) reported a high correlation ($R^2 = 0.84$) between feed-out rates and average seasonal temperatures from 6 countries. Based on their data, it can be inferred that under warm conditions, feed-out rates below 2.0 m/wk do not prevent aerobic deterioration even if good silo management practices are used. As a general recommendation, to

ensure a correct feed-out rate, the daily amount of silage consumed by the herd and the average temperature during the unloading period should be taken into account in advance of silo sizing and filling.

Barriers Faced by Farmers in Hot Regions

Generally, farming systems in tropical regions can be categorized as either low or high input. In high-input intensive systems, the aim is to produce high-quality silage to feed livestock of medium or high genetic merit (e.g., Holstein cattle). In low-input systems, farmers raise native livestock and have a goal of subsistence farming (Adesogan, 2009). Thus, low-input silage production systems are subject to specific restrictions as discussed below.

Economics. Because advanced machines for optimizing silage production are unaffordable in low-input systems, many farmers borrow equipment from neighbors, the municipal government, or cooperatives. This practice can lead to negative consequences because the crop is not always harvested, chopped, transported, and packed properly. Those producers who are able to purchase equipment select simpler, less expensive machines (e.g., harvesters pulled by a tractor). In Brazil, the use of pull-type forage harvesters is still very common (Bernardes and Rêgo, 2014), mainly due to the high cost of self-propelled harvesters. This scenario is different from that observed in other countries with a tradition of conserving forages as silage. According to Muck and Shinners (2001), worldwide sales of traditional machines decreased from 7,000 units in 1990 to 3,500 in 1995, whereas the sales of self-propelled harvesters increased from 1,800 to 2,500 units within the same period. Aside from the ensiling process, the lack of equipment is also reflected during the unloading phase, as many farmers remove silage manually using hand forks or shovels.

Ensiling Expertise. Producers in most tropical low-input systems lack information on the best agronomic and management practices for enhancing silage preservation. In 2013, 260 Brazilian dairy farmers answered a survey asking how often they sharpen the harvester knives (Bernardes and Rêgo, 2014). Only 54.6% of the respondents indicated that they sharpen the knives of the harvesters daily. Half of the farmers reported sharpening only at the beginning of the harvest (26.9%), every 2 d (11.2%), or less frequently than every 2 d (7.3%).

Regarding the filling phase of the silo, a study involving 32 dairy farms in Brazil showed that farmers tend to overfill bunker silos (T. F. Bernardes, I. L. De Oliveira, and L. M. Lima, Department of Animal Science, Federal University of Lavras, Brazil; unpublished data). In this study, overfilled silos had poorer fermentation and higher yeast counts in the upper layers of the mass compared with farms where corn silages were maintained below the sidewalls of the bunker.

With respect to silage sealing, several producers still use black plastic for covering silos (Bernardes and Rêgo, 2014), which is considered to be a poor practice. Snell et al. (2003) reported the effects of color on the temperature of the film surfaces. They determined that during the morning hours, temperature peaks were up to 16°C higher for black film compared with white film. In these systems, several producers also ignored the effects of spoiled silage on feed intake and on the nutritive value of the diet; they did not discard silage with a deteriorated appearance but rather fed it directly to cattle (Bernardes and Rêgo, 2014).

SILAGE MAKING IN COLD REGIONS

Growing forages under cold climatic conditions offers challenges that can vary with high humidity, drought, or short growing seasons. Forage production in cold regions is mostly conducted under short growing seasons and low temperatures, with an annual pattern dominated by a long dormancy period corresponding to the winter months. In some of the less-favored cold regions of North America and Northern Europe, production of forage and associated livestock, including dairy cattle, beef cattle, sheep, goats, and horses, is often the only agricultural activity possible. Short and cool growing seasons along with harsh winter conditions limit the choice of perennial grasses and legumes, which might result in lower nutritive value than in areas with more favorable growing conditions. For instance, the most widely used perennial forage species in eastern Canada and the Nordic countries include timothy (*Phleum pratense* L.), perennial ryegrass (*Lolium perenne* L.), and tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort]. The latter 2 forage species are known for their greater nutritive value and sugar concentration than timothy and are widely grown in the United Kingdom, continental Europe, and the northern United States. However, they have limited acreage in more northern areas of Canada and the Nordic countries because of their lack of winter hardiness. Red clover (*Trifolium pratense* L.), a forage legume species, is widely used in the northern areas of North America and Nordic countries and tends to have a lower NDF concentration and greater DM and NDF digestibilities than alfalfa (*Medicago sativa* L.; Pelletier et al., 2010).

Cold-season grasses and legumes are typically harvested in a bimodal manner that is dictated by season

(Balasko and Nelson, 2003), with high levels of DM production in the spring followed by a second DM production period in late summer to early fall. Most forage species cultivated in cold climates are perennials that have root systems that are able to store energy to enable plant survival over the winter. Winter cereals are also used to improve field management and are sown in the autumn to either germinate after a summer crop or harvest the following spring, before planting of the next seasonal crop.

Winter hardiness could be defined as the capacity of a plant to tolerate freezing and subsequent injury to aboveground tissues and root systems from low temperature and ice. Annual losses in the field due to winterkill of alfalfa can be as high as 78% (Ouellet, 1976). Acclimation to lower temperature is a progressive mechanism that allows plants to survive the winter. One adaptation for survival at low temperatures is that freezing of plant tissues is limited to extracellular spaces. Accumulation of different solutes, such as glycine (Ferullo et al., 1997), protects the cell from desiccation induced by changes in vapor pressure between intra- and extracellular compartments (Belanger et al., 2002).

A longer photosynthesis period due to the Earth's orbital inclination in early summer contributes to the high DM production during this season in colder regions. Most of the sugars produced are used to build structural carbohydrates that increase yield, but some sugars are transported to the roots, where they accumulate in storage structures. For example, timothy accumulates β(2,6)-linked fructans of high degrees of polymerization in its roots (Cairns et al., 1999). Fructans are easily translocated to different organs and can act as defensive molecules that serve as membrane protectors that increase the tolerance of plants to low temperatures (Thorsteinsson et al., 2002; Van den Ende et al., 2004).

The nutritive value of cool-season forage grasses is known to be affected by air temperature, and higher nutritive value is expected when forage crops are grown under the cool conditions (Buxton and Fales, 1994) encountered at higher latitudes. For instance, cool-season grasses generally have a higher concentration of NFC when grown at cool temperatures (5–10°C) than when grown at warm temperatures (15–25°C; Deinum et al., 1968; Chatterton et al., 1989). Low temperatures are also known to improve forage digestibility through a reduction in lignification (Deinum et al., 1981; Thorvaldsson et al., 2007; Bertrand et al., 2008) and a corresponding improvement in digestibility (Thorvaldsson et al., 2007).

The possibility of growing higher yielding annual crops such as corn silage is limited by the short and cool growing seasons in northern areas. Short growing seasons and long, cold winters also limit the grazing season to less than 6 mo in many areas and therefore increase the dependence on conserved forage with a corresponding requirement for harvesting equipment, storage structures, and optimal forage conservation. In most cold and humid regions forages are conserved as silages, and their quality is critical for the feeding of high-quality forages to dairy and beef cattle.

Increasing Sugar Concentration of Perennial Forage Species in Cold Regions

Forage yield, digestibility, CP concentration, mineral composition, and functional compounds are all important attributes that are affected directly or indirectly by climate. This section focuses mainly on nonstructural carbohydrates because along with affecting the feed value, they also affect ensiling potential. Nonstructural carbohydrates are the main source of fermentable substrates during ensiling, and they are an important source of readily fermentable energy for rumen microbes. They include WSC (i.e., glucose, fructose, sucrose, and fructans) and starch. Factors that affect plant growth and metabolism, such as climate, harvest management, and fertilization, are also likely to affect forage NFC concentration. Several strategies exist to increase the concentration of NFC in forages grown in cold areas.

Morning Versus Afternoon Cutting and Swath Management. Plant carbohydrate concentration increases during the day, when photosynthetic carbohydrate synthesis exceeds utilization. This opens the possibility of cutting at a time during the day when NFC concentrations are the highest. Studies conducted with different forage species in North America, including the more northern areas, have shown that cutting later in the day results in forages with greater NFC concentrations, particularly on sunny days (Fisher et al., 1999, 2002; Burns et al., 2005, 2007). The highest NFC concentrations usually occur between 11 and 13 h after sunrise in both alfalfa (Morin et al., 2011) and timothy (Morin et al., 2012a); this optimal time period is the same in spring, summer, and autumn for alfalfa (Morin et al., 2012b).

Plant cells remain viable after cutting and continue to use NFC for respiration until they die. In the northern agricultural area of eastern Canada, alfalfa NFC concentration progressively decreased at a rate ranging from 0.2 to 3.5 g/kg of DM per hour during the first day of wilting (Morin et al., 2012b). This rate of decrease in NFC concentration was not affected by the time of cutting (a.m. vs. p.m.). Consequently, p.m.-cut alfalfa still has greater NFC concentrations than

a.m.-cut alfalfa at the end of the wilting period under optimal drying conditions. It is often thought that PM-cut alfalfa will lose a significant proportion of its NFC during the night, hence losing its advantage over a.m.-cut alfalfa. However, recent research has shown that nighttime NFC losses in late p.m.-cut alfalfa, although variable, are low and that these losses are more than compensated by early morning photosynthesis of cut and unwilted alfalfa. Photosynthesis of late p.m.-cut alfalfa continues for up to 3 h after the morning cutting until DM concentrations reach approximately 350 g of DM/kg (Morin et al., 2012b). The late p.m.-cut alfalfa laid directly on the ground without swathing, having not wilted during the night, can resume photosynthesis the following morning (d 1 of wilting) at the same rate as a.m.-cut alfalfa and standing alfalfa.

Wilting conditions affect forage NFC concentrations. Fast drying reduces respiration time and, consequently, the oxidation of NFC. Alfalfa cut and laid directly on the ground reduces wilting time by up to 9 h under poor drying conditions and exhibits increased NFC concentrations compared with alfalfa that is swathed and dried in windrows. Therefore, late p.m. cutting and wilting of alfalfa in wide swaths are agronomic practices that can be used to increase NFC concentrations (Morin et al., 2012b). When wilting conditions are conducive for rapid drying and with 2 consecutive sunny days, producers using this practice can produce wilted alfalfa forage with greater NFC concentrations in less than 24 h. Some NFC, such as fructans in timothy, are prone to degradation during the wilting period, partly due to higher activities of specific hydrolase enzymes (Ould-Ahmed et al., 2015). Increasing fructose concentration through a reduction in fructan degradation during wilting could improve the ensiling potential of timothy. The metabolic regulation of reserve carbohydrates in forages, such as starch or fructans, is complex and involves multiple genes and biochemical pathways (Ould-Ahmed et al., 2014). Fructans are easily degraded during ensiling (Merry et al., 1995), but the rate of degradation is uncertain because it is not known to what extent fructan exohydrolases remain active during wilting (Ould-Ahmed et al., 2015). The fate of these carbohydrates during ensiling is also unclear; in one study, only 2% of LAB possessed the ability to degrade this polysaccharide (Winters et al., 1998).

Soluble carbohydrates such as glucose, fructose, and sucrose are quantitatively the most important substrates for silage fermentation. Consequently, concentrations of NFC decrease during fermentation, and the extent of this decrease in NFC concentration varies with silage DM concentration. The resulting decrease in NFC concentration during fermentation may offset the gains in nutritive value achieved by harvesting the forage at high NFC concentration. As outlined above, concentration of NFC in alfalfa increases if the alfalfa is cut in the afternoon and wilted in wide swaths. Tremblay et al. (2014) investigated the implication of this practice for silage fermentation. Differences in alfalfa NFC concentration at ensiling (10 to 36 g/kg of DM) due to p.m. cutting, with or without wide swaths, were reduced during ensiling to between 0 and 15 g/kg of DM, mostly as a result of the utilization of NFC. When NFC concentration differences at ensiling due to p.m. cutting were greater than 10 g/kg of DM, silage conservation attributes were improved with lower pH (-0.2 to -0.4), greater concentrations of lactate ($+8$ to $+20$ g/kg of DM), and lower concentrations of VFA (-8 to -11 g/kg of DM) and ammonia nitrogen (-6 to -11 g/kg of total N). Improved silage conservation attributes, along with a greater residual starch concentration from NFC-enriched alfalfa, have the potential to increase the nutritive value of silage and improve milk production.

Species, Stages of Development, and Season. Producers in temperate and cold areas have access to several forage species and mixtures, but there is little information on which species and mixtures result in the highest NFC concentrations. Legumes are often thought of as having lower NFC concentrations than grasses. However, in a study conducted in eastern Canada, alfalfa had similar NFC concentration to timothy (Pelletier et al., 2010). Few studies have compared the NFC concentration among cool-season forage species. The limited available information indicates that red clover has a greater NFC concentration than alfalfa and that tall fescue has the highest NFC concentration among several cool-season grasses (Pelletier et al., 2010).

The NFC concentration may vary with stage of development at harvest, but results are inconsistent, partly because of the confounding effect of the climatic conditions on or near the time of harvest (Wilman, 2004). In a study conducted in the most northern agricultural area of eastern Canada ($\sim$1,400 growing degree days), there were no consistent differences in forage NFC concentrations in tall fescue cut 2, 3, or 5 times per year (Drapeau et al., 2005). Shorter intervals between harvests did not influence NFC concentrations. However, in the fall, delaying harvest can result in significant increases in NFC as ambient air temperatures decrease. In the most northern agricultural area of eastern Canada, the NFC concentration of tall fescue increased from 60 g/kg of DM in early September to 150 g/kg of DM in late October (Drapeau et al., 2007). At less than optimal temperatures for growth, carbohydrates accumulate as photosynthesis generates NFC that are not immediately incorporated into plant tissues due to

declining growth rates (i.e., photosynthesis continues at the same rate while growth slows).

Differences in NFC concentrations between spring and summer varied with the forage species in a study conducted in eastern Canada, and no general conclusions could be drawn (Pelletier et al., 2010). However, alfalfa harvested in early October had a greater NFC concentration than that harvested in June or August (128 vs. 91 and 102 g/kg of DM, respectively) in an eastern Canadian study in a region with 1,700 growing degree days (Morin et al., 2012b). Perennial forage crops harvested in late fall (e.g., October in eastern Canada) are likely to have much greater NFC concentrations than those harvested in summer or early fall.

Nitrogen Fertilization. Lowering N fertilization has been shown to increase NFC and reduce CP concentrations of several cool-season grass species—for example, timothy, orchardgrass (*Dactylis glomerata* L.), and tall fescue (Pelletier et al., 2009)—but it may also reduce total yield. Timothy silage quality is reduced by increased application of N fertilizer, primarily at early developmental stages, and this can be attributed to a reduction in WSC concentration and an increase in the buffering capacity of the forage. Therefore, the ensiling properties of timothy are less favorable when high rates of N fertilizer are applied (Tremblay et al., 2005).

Producing Corn Silage and Other Silage Crops in Cold Areas

Corn growth and development are very sensitive to temperature. Corn is also sensitive to late spring frosts and early fall frosts. A short growing season and cool temperatures often limit the use of corn silage in cold areas. The successful introduction of short-season corn hybrids along with the current and projected warming of the climate has raised the interest in growing corn for silage in cold areas and could potentially open up large northern areas for corn silage production.

When grown in cool climates, short-season hybrids often fail to reach the recommended 340 g/kg of whole-plant DM concentration before fall harvest (Ma et al., 2006). Ensiling immature corn forage in tower silos can result in excessive seepage losses and even freezing, and feeding immature corn silage can have negative effects on voluntary intake.

Harvest of corn silage is often delayed to obtain an adequate DM concentration. Producers in cold areas often use frost as a means of increasing DM concentration so that corn can be ensiled. These practices can affect feeding values of the forage. Calder et al. (1977) reported an 8% decrease in the DM digestibility of corn harvested after the first frost. Decreases in nitrogen,

phosphorus, and potassium have also been observed after the first frost (White et al. 1976). Although these authors did not mention the severity of the frost events, St Pierre et al. (1987) observed that exposing corn to up to 2 frosts resulted in higher silage intake and 4% FCM production. In a study conducted in a region with fewer than 2,300 corn heat units in Québec, Canada, delaying the harvest by 31 d after the first frost increased the DM concentration from 306 to 461 g/kg of fresh matter (Drapeau et al., 2002). However, delaying the corn harvest until after the first frost was shown to decrease yield by 38 kg of DM/ha per day and to increase the NDF concentration by 0.68 g/kg of DM per day. These changes in yield and nutritive value translate into a reduction in estimated milk production of 68 kg/ha for each day of delayed harvest (Drapeau et al., 2002). Early fall frosts of corn may also reduce the level of beneficial silage bacteria (primarily LAB) on the standing plant and elevate numbers of spoilage organisms such as yeasts and molds. However, frost-damaged corn can still be ensiled even without the use of inoculants (Mohammadzadeh et al., 2012, 2014).

Reed canary grass (*Phalaris arundinacea* L.), a high-yielding cool-season grass species recommended for forage production in the northern areas of North America, and switchgrass (*Panicum virgatum* L.), a perennial warm-season grass species native to the North American prairies, are also potential perennial herbaceous biomass crops for energy production. These grass species are likely to be conserved as silage before their use in anaerobic digesters for methane production and even for cellulosic ethanol production. Although their ensiling potential as forage crops is relatively well known, very few studies have looked at their ensiling potential when harvested once a year late in the season. Results from studies conducted in eastern Canada confirm the high yield and ensiling potential of both species as an energy crop in northern latitudes. Silage attributes (pH and concentrations of lactate and ammonia nitrogen) also reflected adequate fermentation during ensiling (Belanger et al., 2012, 2016).

The growth potential of sweet pearl millet [*Pennisetum glaucum* (L.) R.Br] and sweet sorghum [*Sorghum bicolor* (L.) Moench] under the cool and humid conditions of eastern Canada was also demonstrated in recent years. Both forages were deemed to have potential as sources of biomass for biofuel production due to their high sugar yields. The bagasse produced as a result of the extraction of the NFC from these forages for ethanol production could also be preserved as silage and used as an animal feed. Presently, the nutritive and conservation attributes of bagasse silage from sweet sorghum and sweet pearl millet grown in the northern

areas are not well known. A recent study showed that extraction of the NFC from the biomass of sweet pearl millet and sweet sorghum reduced the nutritive value of the residue but did not impair its ability to be ensiled (Dos Passos Bernardes et al., 2016).

Effects of Cold Conditions on Silage Conservation

For most of the growing season, ensiling conditions at northern latitudes are conducive to the production of silage. Ambient temperatures are usually above 15°C during the day but still can decrease significantly during the night. These fluctuations in temperature can cause the formation of dew, which increases surface moisture on the wilted forage. Although there are no published results on the effect of dew on the microbial community, prolonging wilting will have a negative effect on the residual carbohydrates, lipids, and protein content of the forage (Papadopoulos and McKersie, 1983; Liu et al., 2011; Edmunds et al., 2012; Van Ranst et al., 2013).

Harvesting forages at the northern limits of their cultivation (e.g., corn) can also make these forages more difficult to ensile. As the temperatures decline in the fall, the cool nights and often frequent frosts result in a decline in the metabolic activity of the forage as the plant enters senescence. This influences the epiphytic bacterial population, as freezing can lyse plant cells and release soluble carbohydrates (Melick and Seppelt, 1992) that are metabolized by the plant microbiome (Sanaullah et al., 2010). The lower mean daily temperature can also negatively affect the fermentation process (Ali et al., 2015). Some silage additives can be functionally impaired at lower temperature because strains within silage inoculants are often selected at temperatures associated with warmer climates (Weinberg and Muck, 1996).

A study performed on corn incubated at different temperatures, from 25°C down to 5°C (Zhou et al., 2016), observed significant delays in the pH decline with decreasing temperatures during ensiling, although the terminal silage pH after 60 d was unaffected by temperature. Mini silos incubated at 5°C had a mean pH level of 5.0 after 30 d of fermentation. The diversity of the LAB population as determined by PCR–denaturing gradient gel electrophoresis, suggested that 15°C might be the lower limit for growth of L. buchneri. Still, other heterolactic species dominated the LAB population after 60 d of fermentation at temperatures below 15°C (Zhou et al., 2016). In this study the silage was not inoculated, so these observations were related to the epiphytic LAB population originally associated with the corn forage.

Studying the effect of low temperatures on the fermentation potential of TMR silages ensiled during spring, summer, fall, or winter, Cao et al. (2011) observed that LAB counts and corresponding activities were lower for silages prepared in winter. As silages were stored outdoors, ambient temperature changed daily, reaching a minimum of −2°C. For most conditions, the initial pH of the TMR silages was between 5.22 and 5.44 and decreased by 1 log under moist conditions after 60 d of fermentation. The degree of decline in pH was even lower under colder conditions.

Ensiling wheat straw (32% DM) at 5°C for 30 or 60 d and inoculating it with L. plantarum strains selected for growth at low temperatures improved silage fermentation compared with a control strain (Zhang et al., 2017). Another study of ensiling at low temperature was undertaken by Wang et al. (2011), who investigated the effects of LAB inoculants on the fermentation quality of reed grass (Phragmites australis Cav. Trin. ex Sterd.). Two fermentation conditions were tested: 0 and 4°C. As expected, lower temperatures slowed the rate and extent of fermentation. However, some of these negative outcomes were reversed after 6 wk of ensiling if the silage was inoculated with the LAB inoculant at 6.63 log cfu/g of forage (Wang et al., 2011).

Constraints and Potentialities of Round Bale Silage in Cold Regions

Round bale silage has become a common method of forage preservation in northern climates, particularly in Northern Europe. For example, in Finland approximately one third of grass silage is conserved as round bales (J. Nousiainen, Valio Ltd. Farm Services, Valio, Finland; personal communication), and in Sweden this method accounts for as much as 50% (R. Spördly, Swedish University of Agricultural Sciences, Uppsala, Sweden; personal communication) of the conserved forage. Round bale systems have advantages over chopped silage systems, such as a lower capital investment and flexibility in feeding (Muck and Shinners, 2001). The system is also more flexible when the distance from the field to the point of feeding is longer. In field trials, preservation as round bale silage reduced DM losses and improved nutritive value compared with hay (Han et al., 2004). Wilting, treatment with additives, chopping, and increased bale density (Jonsson et al., 1990; Han et al., 2004; Slottner and Bertilsson, 2006) can also result in improved silage quality.

The results of analysis of on-farm silage samples in Finland indicated that the fermentation quality and nutritive value of round bale silages are comparable to that of silages preserved in bunker silos (Table 1). The concentration of DM was greater in round bale silages than in bunker silo silages, which explains the higher pH and less extensive fermentation. Both silages

were of high quality as reflected by low concentrations of ammonia nitrogen. The variables of nutritive value were similar between the 2 ensiling methods, indicating that on average the silages were harvested at the same stage of maturity (Table 1).

Although new equipment can improve fermentation efficiency by generating bales with a higher density and enabling the chopping of the forage, bales still usually have a lower density than forage packed in bunker or pile silos. The higher oxygen concentration inside bales can delay the fermentation, enabling more sugars to be metabolized by plant cells.

Good-quality baling should be performed at a higher DM level to improve long-term storage. The ideal DM range should be between 400 and 450 g/kg of forage. This range is ideal for LAB and will limit the growth of several undesirable microorganisms (McEniry et al., 2008). Frequently, bales of higher DM level are generated on farms. As a result the elevated osmotic pressure negatively affects the activity of LAB, generating a higher pH that allows the growth of yeasts and molds.

Daily changes in ambient temperature can also promote condensation on the inner layer of plastic, creating conditions that are favorable for the growth of yeast, molds, or other spoilage microorganisms (McEniry et al., 2008). Bales have a higher surface:volume ratio than bunker silos and, as a result, core temperatures in bales decline more rapidly than in bunker silos. This lower internal temperature can affect the microbial succession and metabolism of microorganisms during ensiling (Forristal and O'Kiely, 2005).

Stretch film plastic used to wrap bales is sensitive to physical damage, either from handling or from animals. Generally, silage bales wrapped with 6 layers of stretch film were more secure against physical damage during bale handling than bales with fewer layers (O'Brien et al., 2007). Oxygen ingress will promote deterioration of the silage, promoting the growth of aerobic spoilage microorganisms in localized regions. Clostridia can also become established if regions within the bale exhibit the elevated pH that allows their growth (Jonsson et al., 1990).

Improving Silage Fermentation Through Acid-Based Additives in Cold Regions

Using acid-based additives to control silage fermentation originates from the classical work by Virtanen (1933). His method was based on reducing herbage pH below 4 by direct applications of mixtures of sulphuric and hydrochloric acids. The idea was that direct acidification prevented clostridial fermentation and reduced proteolysis. The corrosive nature of inorganic

Table 1. Composition and fermentation quality of on-farm silage samples in Finland from 2014 to 2016

Item, g/kg of DM unless stated	Round bale	Bunker silo
No. of samples	35,593	21,505
DM, g/kg as fed	369	301
pH	4.33	4.00
CP	137	142
NDF	533	531
Indigestible NDF	75	73
Lactic acid	41	56
VFA	11	16
Ammonia N, g/kg of N	44	42
OM digestibility, g/kg	722	725

acids eventually led to the abandonment of inorganic acids as silage preservatives. Research in Norway (Saue and Breirem, 1969) demonstrated the effectiveness of formic acid, which rapidly became the most commonly used acid-based silage additive. Low (2–2.5 L/t) levels of formic acid favor the growth of epiphytic LAB and facilitate the rapid decline in pH, reducing proteolysis. At high (4–5 L/t) rates of application, direct acidification restricts fermentation, thereby increasing the concentration of residual WSC. The study by Jaakkola et al. (2006) clearly demonstrated the effects of increased application rates on silage fermentation quality. The lowest level (2 L/t) slightly decreased the extent of fermentation and considerably reduced acetic acid production and proteolysis. Higher levels (4–6 L/t) of formic acid further restricted the extent of fermentation and proteolysis and resulted in the highest concentration of residual WSC.

Formic acid has a selective bactericidal effect, but it is not particularly effective against yeasts (McDonald et al., 1991). Even a small amount of oxygen may initiate the growth of the yeasts and molds that are responsible for aerobic deterioration. The use of combinations of hexamethylene tetraamine, sodium nitrite, sodium benzoate, and sodium propionate has improved the quality and storage stability of silage made from wilted grass (Lingvall and Lättemäe, 1999; Knicky and Spörndly, 2009). Currently, when wilting is a common practice, most commercial acid-based silage additives contain propionic acid, benzoic acid, or other organic acids that are more effective against yeasts and molds.

In addition to ensuring good fermentation quality and smaller ensiling losses, acid-treated silages affect both total nutrient intake and the profile of absorbed nutrients. According to a meta-analysis by Huhtanen et al. (2007), silage DMI is negatively influenced by the total acid concentration in silage. In this analysis, the effect on DMI did not differ between homolactic and heterolactic silage fermentations. However, according to Eisner et al. (2006), the predicted intake

Table 2. Effects of total acid concentration in silage (g/kg of DM) when analyzed with univariate or bivariate analysis[1]

Item	Univariate model			Bivariate model		
	Estimate	SE	P-value	Estimate	SE	P-value
Milk, kg/d	−7.3	2.4	0.003	0.8	0.98	0.78
ECM, kg/d	−18.6	2.6	<0.001	−5.8	3.0	0.05
Milk composition, g/kg						
Fat	−0.030	0.003	<0.001	−0.029	0.004	<0.001
Protein	−0.015	0.0019	<0.001	−0.032	0.005	<0.001
Yield, g/d						
Fat	−1.06	0.12	<0.001	−0.47	0.13	0.003
Protein	−0.50	0.08	<0.001	−0.19	0.1	0.07

[1]In bivariate analysis, silage DMI was used as a covariate. Data from Huhtanen et al. (2003).

of silages undergoing a secondary fermentation can be improved by including acetic acid or VFA in the model (Eisner et al., 2006). The mechanisms of increased DMI of acid-treated silages with restricted fermentation are not entirely known. Reduced DMI of extensively fermented silages can be related partly to palatability attributes and partly to the changes in the profile of absorbed nutrients. The efficiency of microbial protein synthesis is lower in animals fed extensively fermented silages (Harrison et al., 2003; Jaakkola et al., 2006), resulting in a lower AA:ME ratio in absorbed nutrients. Similarly, high-quality protein supplements result in increased silage DMI (e.g., Oldham, 1984). Another possible mechanism suggested by Allen et al. (2009) is the hepatic oxidation theory. Of the fuels metabolized in the liver of ruminants, propionate produced from silage lactate is likely a primary satiety signal because its flux to the liver increases with each meal. Propionate is utilized for gluconeogenesis or oxidized in the liver and stimulates the oxidation of acetyl CoA.

The extent of in-silo fermentation of WSC has a strong influence on ruminal fermentation patterns. Increased concentration of silage lactic acid increases propionate concentrations in the rumen. Intraruminal infusions of lactic acid demonstrated that propionate is the main end product of lactate fermentation (Jaakkola and Huhtanen, 1992; Choung and Chamberlain, 1993). Increased lactic acid concentration in silage consistently results in increased propionate concentrations in the rumen (Harrison et al., 2003), whereas higher WSC concentrations in silages treated with formic acid tend to increase either ruminal acetate or butyrate.

The end products of silage fermentation (lactic acid, VFA) provide little or no ATP for rumen microbes (Chamberlain, 1987). As a result of a higher concentration of WSC in silages treated with formic acid, ruminal microbial protein synthesis is increased compared with more extensively fermented silages (Harrison et al., 2003; Jaakkola et al., 2006). In addition to greater ATP

supply from restrictively fermented versus extensively fermented silages, microbial growth can be stimulated by a more optimal N profile in the silage, especially by higher concentrations of peptide N (Nsereko and Rooke, 2000).

A meta-analysis of data from studies investigating the effects of the extent of in-silo fermentation manipulated by different additives (Table 2; Huhtanen et al., 2003) indicated that an increased concentration of total acids in silage was associated with reduced yield of ECM, milk fat, and protein, but yield was unaffected. Milk concentrations of fat and protein decreased with increasing total acid concentration in silage. These changes can be attributed to the total energy supply and changes in the profile of absorbed nutrients. Higher milk fat concentration with restrictively fermented silages is related to increased proportion of lipogenic VFA in rumen fluid, and the higher milk protein concentration is linked to an increase in DMI and improved efficiency of microbial protein synthesis. However, when DMI was used as a covariate in the model, only the effect on milk fat concentration and yield of ECM remained statistically significant, suggesting that DMI was the main driver of production responses in cows fed different silages.

In conclusion, although the use of bacterial inoculants as silage additives has increased in Northern Europe, acid-based additives are still a good option, especially in difficult weather conditions, to ensure good fermentation quality and high intake potential and nutritive value of silages.

FINAL REMARKS

Climatic conditions affect all stages of silage production and utilization, from the field to the feed bunk. All abiotic components can influence silage quality; however, among them, temperature (high or low) seems to be the most limiting factor. Although the availability of

financial resources is not directly affected by climate, in hot regions there are more low-input farming systems, which can also impair silage quality.

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