Particle size effects of forages on the ensiling process and animal performance

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Introduction

Depending on the ensiling method, forages are chopped to various degrees prior to ensiling. Chopping of the plant material influences the ensiling process, and has direct and indirect effects on performance of the animals consuming the silages. The objective of this paper is to elucidate the basis of these effects on ruminant nutrition and review the results from experiments of this topic with main emphasis on dairy cows.

The theoretical benefits from shorter chop length on silage preservation are clear (McDonald et al., 1991). In practical silage making, chop length is confounded with other factors such as rupturing of plant cells, and degree of compaction and sealing after ensiling. Preserving forages precision-chopped in well compacted and sealed bunker silos provides sound foundation for good anaerobic fermentation and minimal losses. Short chop length is however not a prerequisite for good fermentation quality as longer particle size forages also have good ensiling quality when silage raw material is of good quality and ensiling techniques are correctly applied. Good fermentation quality of silage is reflected in high feed intake and productivity of animals and low risks of contamination of animal products with potential feed originated micro-organisms such as *Listeria* or spores of butyric acid bacteria.

Forage particle size also affects animal performance. The effect of diet particle size on dairy cow digestion and performance has been extensively studied. Feed intake and subsequently animal productivity often increase in response to smaller feed particle size, but sometimes these positive effects can be compromised by lack of adequate physical structure in the diet and decreased rumen pH. The main drivers for the research have been to prevent milk fat depression and subacute ruminal acidosis (SARA).

The ample availability of low price feed components such as cereal grains and by-products provide large amounts of easily fermentable carbohydrates into ruminant diets. In many areas globally, the main task of ration formulation is to maximize the intake of easily fermentable carbohydrates without posing a risk to animal health, welfare and longevity. This is somehow controversial, because the main evolutionary benefit from ruminants is their ability to use fiber as a source of nutrients. This discrepancy creates need to study forage particle size and other factors contributing to the maintenance of normal rumen function.

Defining and determining particle size is equivocal. Several methods including dry or wet sieving according to variable protocols, microscopic image analysis or laser diffraction have been used for particle size determination (Kennedy, 2005), although physically effective fiber (see Mertens, 1997; Kononoff et al., 2003a) is widely used in scientific literature. The different methods are typically not interchangeable, which complicates the interpretation of various experimental results. In the current review, no attempts were made to standardize the particle sizes reported in various articles, but they are used as reported in the original source. The term "particle size" has been used to replace the variable terms in literature such as particle length or theoretical length of cut.

Effect of forage particle size on silage preservation

Chopping and other physical damage such as maceration, bruising, and mincing improve substrate availability to lactic acid bacteria, contribute to more effective compaction and oxygen removal and thus result in fast homofermentative lactic acid fermentation of the plant material (McDonald et al., 1991; Pauly et al., 1999: McEniry et al., 2008). Chopping may also facilitate an even dispersion of additives within the forage material.

There are several different technical solutions available for silage making resulting in significant differences in the chop length of the final forage. Precision-chopping results in the shortest chop length (typically <35 mm), while big balers and forage wagons can conserve forage without any chopping. Typically big balers and forage wagons are equipped with cutters which cut the forage to a variable degree. Crop characteristics, harvesting methods and machine settings will affect the mean particle size and variability achieved (Shinners, 2003). Forage material prepared by any method includes an array of particles of different sizes, and it can be described as a curve (Figure 1). The particle size may also be affected by the driving speed as Suokannas and Nysand (2008) reported a clear reduction in particle length, when the driving speed of a forage wagon equipped with cutters was increased.

Changes in chop length in practical silage making are typically confounded with other changes including the effect of forage dry matter (DM) concentration (forage ensiled in bunker silos has typically lower DM concentration than in big bales), level of cell rupturing and qualities of the storage (type of silo/clamp, bale etc. including differences in compaction/density and air infiltration). The mechanical effects of harvesting machinery on forage material can be divided into reduction of chop length, which improves compaction and obtaining homogeneous forage mass, and rupturing forage cells, which releases cell saps providing substrates to lactic acid bacteria. Pauly et al. (1999) measured the electric conductivity of water extracts from long, cut and precision-chopped grass, and found a 4-fold increase in precision-chopped *vs*. the other treatments indicating greater release of cell saps in precision-chopped material.

Decreasing forage particle size at harvest increases energy consumption of the machinery (Shinners, 2003). Suokannas and Nysand (2008) reported a 65 % higher energy consumption for the cutting function of a precision-chopper compared to that of loader wagons. On the other hand, decreasing forage particle size at harvest may facilitate total mixed ration (TMR) preparation by reducing the power requirements, and loading and mixing time. Basically the same phenomenon can be realized when animals are consuming the feed – eating time is typically shortened when finely chopped feeds are given to animals (see section on feeding behavior).

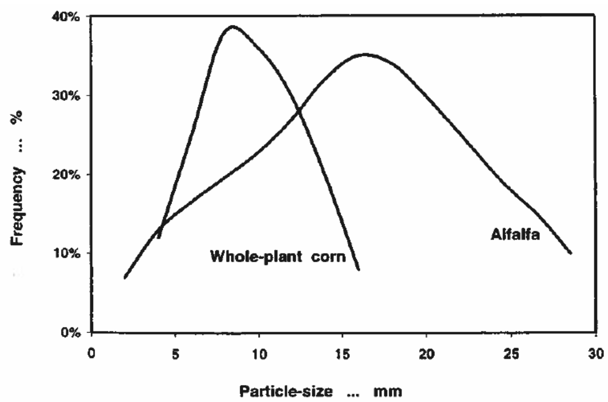

Figure 1. The same theoretical length of cut (10 mm) produces variable mean and variation in particle size depending on forage crop (Shinners, 2003).

Grass silages

In a review by Haigh (1998) including 21 experiments in UK, grass silages produced by flail harvester, forage wagon, double-chopper or precision-chopper were compared. The shorter the chop length in the harvesting system, the better the preservation quality and animal performance as precision-chop silages ranked typically first and those harvested with forage wagon last. Similarly, Petit et al. (1993) reported highest DM intake and milk production in precision-chopped silage followed by silages harvested using forage wagon or big baler. In Scandinavia there is a long tradition in producing high quality grass silages using direct-cut flail-harvested silages with ca. 200 g/kg DM concentration with the aid of using relatively high levels of formic acid (4 l/per ton fresh grass) in additives. Other methods such as wilted precision-chopped and big-baled silages have however taken over nowadays with important benefits in capacity compared with flail-harvesters.

Forages conserved in big bales or picked up by forage wagons may be in the long form without reduction in particle size, but currently it is common to include cutters to them in order to increase silage density, and facilitate the use of silages at the feeding phase (Shinners, 2003). It has not been very easy to show experimentally improvements in bale silage fermentation quality in response to decreased chop length (Borreani & Tabacco, 2006; Müller, 2009). Addition of knives into forage wagons did also not improve the fermentation quality of grass silage in the experiment of Pauly and Lingvall (1999), although grass chop length was markedly decreased. The chop length effects were also minimal in the experiment of Paziani et al. (2005) using tropical Tanzania grass as the raw material.

McEniry et al. (2007) demonstrated that DM concentration and air infiltration had greater effects on grass silage fermentation quality and losses than chopping or compaction. In a later study (McEniry et al., 2008), unchopped and precision-chopped ryegrass were compared in laboratory silos with faster fermentation and improved final fermentation quality of precision-chopped *vs*. unchopped silage. Pauly et al. (1999) reported faster onset of fermentation and less heterogeneous forage mass of precision-chopped *vs*. unchopped or cut silage in laboratory silos, which resulted in a better preservation of precision-chopped silage (Figure 2). If moist silages are ensiled, chopping will increase effluent losses (McDonald et al., 1991; McEniry et al., 2008).

Precision-chopped silages seem to have an advantage compared to unchopped grass or grass cut by big balers or forage wagons. The faster onset of fermentation is probably related to the cell ruptures and not solely to particle size. Further, the storage conditions in bunker silos, which is the most typical storage method for precision-chopped silage, are typically more favorable (higher density, less aerobic exposure than in big bales). The particle size *per se* probably has a small independent positive effect on the ensiling process, but it is not an absolute prerequisite for good fermentation quality as good quality silages can be produced by all typically used methods, when appropriate ensiling methods are used. The method chosen on a particular farm must fulfill the economic and other management needs, which may override the differences between the biological ensiling characteristics of the methods (Muck and O'Kiely, 2002).

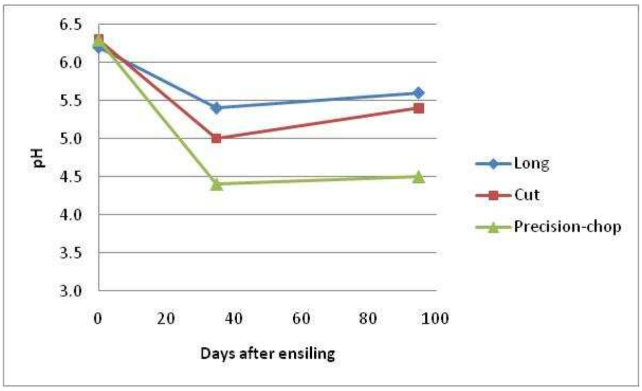

Figure 2. The development of grass pH after ensiling in the study of Pauly et al. (1999) demonstrate the benefits from precision-chopped *vs.* cut or long material. The average particle lengths were 30, 40 and 230 mm, respectively.

Whole crop cereal silages Corn (maize) silage is an important raw material for preparing whole crop cereal silage. It is typically harvested with a self-propelled chopper directly from the standing crop equipped with a head for chopping corn. This method produces rather short chop. Several studies have evaluated the effects of chop length and other mechanical treatments on corn silage and benefits in ensiling quality have been achieved with more aggressive treatments (Johnsson et al., 2002, Hara & Tanigawa, 2010), although differences have not always been observed particularly if also the control treatment has been well preserved [e.g. Fernandez et al., 2004; Cooke & Bernard, 2005; Yang and Beauchemin, 2006 (barley silage)].

The preferable harvesting method for small grain cereals is using a chopper, which harvest directly the standing crop. Sometimes cereals like barley or wheat are also ensiled in big bales, although first mowing and then picking up often increases the kernel losses to unacceptable levels. The compaction of the bales may also be poor and hard stems may penetrate the plastic thus leading to air infiltration into the bales. Ohlsson (1998) reported benefits in bale density and fermentation quality, when barley was cut using a precutter before ensiling in round bales, but simultaneously the losses of kernels increased.

Aerobic stability Aerobic stability describes the time that silage remains stable (typically measured as a maximum of 2 ˚C rise compared to the ambient temperature) when exposed to oxygen at feedout. Aerobic deterioration may cause large DM losses and reduced animal performance (McDonald et al., 1991; Kung, 2005)

The risk factors for poor aerobic stability are contamination of the crop with aerobic microbes and air infiltration into the silage mass enabling survival and growth of aerobic microbes. Porosity of compacted plant material contributes to gas flow and air infiltration rate with consequent increases in DM losses due to aerobic deterioration as emphasized by Holmes and Bolsen (2009). Porosity increases with increasing DM concentration of forage and it could be expected to decrease in response to shorter chop length and subsequent more effective compaction. McEniry et al. (2007) found no effect of grass chop length on aerobic stability, while in the later study (McEniry et al., 2008) precision-chopping decreased the time to temperature rise >2˚C compared to unchopped grass. Both long and cut silages prepared by Müller (2009) remained stable for the 5-day observation period.

Effect of particle size on animal performance

Indirect effects of feed particle size on animal performance The various experimental situations require consideration because particle size and fermentation quality of silages may be confounded. The data set of Haigh (1998) is a good example of this: Precision-chopped silages gave best animal production results and had the shortest chop length, but were superior also in preservation quality.

If only the effect of particle size is to be evaluated, the particle size of experimental feeds needs to be manipulated just prior to feeding so that chopping has not influenced the preservation of the silage. Sometimes the treatments may also have other differences if e.g. treatments have resulted in variable shredding losses in the field so that the nutritional composition and digestibility differ between treatments.

Determination of particle size and physical structure of the diet In order to produce benefits in practical ration formulation, the system describing the physical effectiveness of diet must have close correlation to animal performance, and the values for farm feeds need to be readily accessible. De Brabander et al. (1999) recognized the challenge in defining the physical structure but presented the following description of it: “The extent to which a feedstuff, through its content and properties of the carbohydrates, contributes to an optimum and stable rumen function”. Particle size is one of the factors contributing to the physical structure.

Several systems have been developed to assist in formulating diets adequate in physical structure. Sudweeks et al. (1981) developed a roughage value index based on mean diameter of the feed determined by sieving, DM intake and fiber concentration. The index values range from ≈10 min/kg for concentrate feeds to up to ≈100 min/kg for low quality forages, and a minimum value of ≈30 min/kg for the diet was recommended to maintain milk fat concentration at normal levels.

Mertens (1997) introduced physically effective neutral detergent fiber (peNDF), which is based on neutral detergent fiber (NDF) concentration and the relative effectiveness of NDF in promoting chewing activity. The peNDF is measured by dry sieving so that NDF concentration of particles retained on a 1.18 mm sieve is considered physically effective, and the Penn State Particle Separator is widely used in measuring it (Kononoff et al., 2003a). The peNDF is presented in proportional values (0 to 1) providing a more consistent measure than the roughage value index, which is also influenced by animal factors. Mertens (1997) listed that on top of particle size, other factors such as DM intake, particle shape, fragility, moisture, type of preservation, and ratio of eating time to rumination time contribute to the physical effectiveness of fiber.

De Brabander et al. (1999) examined the required physical structure of various dietary components. Particle size of grass silages did not have an effect on the critical amount of roughage required in the diet to maintain normal rumen functions, whereas for corn silage, increasing particle size increased the structural value, probably because of the smaller average particle size in corn silages. Fiber (as NDF of crude fiber), effective fiber measures or feeding behavior did not produce consistent relationships with the amount of roughage needed to maintain the normal rumen functions. De Brabander et al. (1999) proposed a derived unit, which takes into account both feed characteristics (e.g. concentration of fiber, particle size and acidotic effect) together with feeding management (i.e., number of concentrate meals per day) in order to formulate dairy cow rations for good rumen function. Nørgaard et al. (2010) presented the Nordic structure evaluation systems for dairy cows, where particle size also is considered.

Feed intake and animal performance

Increased feed intake is often observed, when forage particle size decreases (e.g. Kononoff et a., 2003b; Tafaj et al., 2007; Zebeli et al., 2009). The effect has been shown also in experiments, where the forage has been chopped to variable lengths just prior to feeding to avoid the confounding effect of chop length on fermentation quality. In the meta-analysis of Tafaj et al. (2007), the DM intake increased by 80 g/day when forage particle length decreased by 1 mm. Production responses could not be demonstrated, but decreasing particle size decreased rumen pH, and chewing and rumination time.

In situations where physical limitation is more important (grass rather than corn silage based diets, low proportion of concentrate in the diet), decreasing forage particle size is more likely to increase feed intake. The results from Castle et al. (1979) demonstrate a greater intake response to chopping of silage when silage was fed as a sole feed compared to a situation when also concentrate was included in the diet, which is explained by the decreased physical limitation of the diet including concentrates.

Increased feed intake typically results in increased production of the ruminants. However, if it is accompanied by decreased fiber digestibility, benefits from increased intake may partially or totally be lost (see later section on fiber digestion).

Feeding behavior

During ingestive mastication, feed particles are reduced in size and lubricated with saliva to prepare the bolus for swallowing. During rumination, saliva production is stimulated, and particles are further decreased in size and their relative specific gravity increases, which are essential characteristics in facilitating their passage from rumen to the lower digestive tract (Kennedy, 2005).

Decreasing particle size typically decreases chewing time during eating and/or ruminating, and subsequently total chewing time (Allen, 1997; Couderc et al., 2006; Yang & Beauchemin, 2006, 2009; Tafaj et al., 2007, Figure 3), although the relationship was not very clear in the dataset of De Brabander (1999). The changes in eating behavior are not always reflected in changes in rumen pH and animal performance.

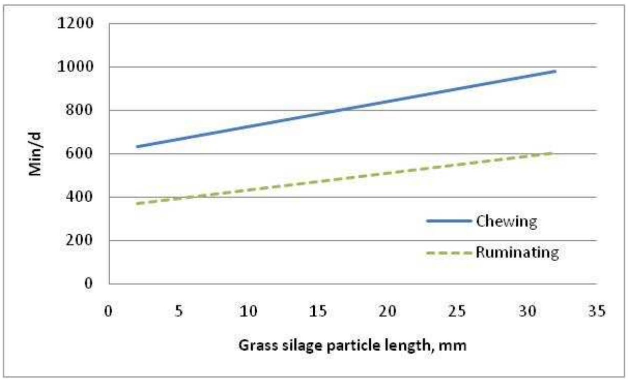

Figure 3. Increasing particle length linearly increased chewing and rumination times of dairy cows fed grass silage based TMR in the meta-analysis of Tafaj et al. (2007). Total chewing time increased by 11.7 min and rumination time by 7.6 min per 1 mm increase in grass silage particle size. The particle size effect on feeding behavior was not significant when corn silage based TMR was fed.

In theory, increased mastication may be considered as a loss of energy for the cow, which is compensated by less mechanical work required in feed preparation. Long chewing times may at least theoretically also compromise feed intake, because cows need to allocate part of their time for resting. Mertens (1997) proposed a maximum chewing time of 1000 min per day. There is a large variation in chewing times [average 668 min/d with a range of 364 to 962 in the data set of Allen (1997), and average 694 min/d with a range of 424 to 969 in the data set of Tafaj et al. (2007)]. Teller et al. (1993) presented a mean chewing time of 948±45 min/day for 16 silage-based diets and depicted that the total number of jaw movements during eating and ruminating is approximately 60 000 per day. They proposed that genetically determined physical characteristics for efficient forage ingestion and chewing should be considered in animal breeding programs.

The effect of particle size on chewing time seems to be curvilinear. Allen (1997) studied the relationship between particle size and daily chewing time using data from 10 dairy cow experiments and found that a particle size threshold occurred at approximately 3 mm sieve, above which forage particle size did not further increase chewing time. Similarly, dramatic changes in chewing time were achieved when reduction in grass particle size <3 mm was used (Tafaj et al., 2007). According to De Brabander et al. (1999) particle size did not affect the structure value of normal grass silages in practice with a particle size above 20 mm.

Particle size may affect the proportion of rumination in total chewing time. Allen (1997) reported that the proportion of rumination in total chewing time was 0.60 with a range from 0.43 to 0.74. The proportion of rumination time decreased when long hay *vs*. chopped forage was fed and when fiber concentration of forage increased, as these factors increased chewing during eating, although in absolute terms, also time spent ruminating increased. The equations of Tafaj et al. (2007) show practically no trend in the proportion of rumination in total chewing time (0.59 and 0.61 for diets with forage particle lengths of 2 and 32 mm, respectively; Figure 3). Reduced eating time could be considered beneficial in situations where feed bunk place is limited. Fast eating could particularly benefit animals low in social hierarchy, which may have problems in accessing the feed bunk.

There is large variation in the feeding behavior between cows. Almost half of the variance in feeding behavior, and 0.21 of critical roughage value could be explained by differences between cows in the data set of De Brabander et al. (1999). Currently there are equipments available that under practical farming situations register the chewing time of cows. Probably the best use of such equipments is to detect deviations from normal behavior rather than indicating adequate physical structure in the diet.

The salivary secretion rates during resting, eating and ruminating were estimated by Cassida and Stokes (1986) to be 0.15, 0.18 and 0.27 liters per min. emphasizing the role of rumination in buffering rumen pH. This is also depicted by the clearly visible increases in rumen pH during rumination bouts (Allen, 1997; Figure 4). Beauchemin et al. (2008) measured salivary secretion during eating of four clearly distinct forages (no direct comparison of particle size) and found similar rate of saliva secretion during eating (0.21 kg/min). The rate of chopped barley straw eating was slower than that of the other forages (barley silage, alfalfa silage and long alfalfa hay) so that per rate of DM intake, it was mostly salivated, but when expressed per kg NDF, alfalfa hay was mostly salivated. The rate of saliva production per kg pelleted concentrate DM consumed was only one fourth of that of the average of the four forages (Beuchemin et al., 2008). Faster eating rate of chopped forages would decrease their salivation during eating, but the changes on total saliva production are probably more related to the time spent ruminating.

Teller et al. (1993) speculated that longer eating time may restrict the time available for rumination, which – because of the greater rate of saliva production during ruminating compared to eating – might predispose to low ruminal pH.

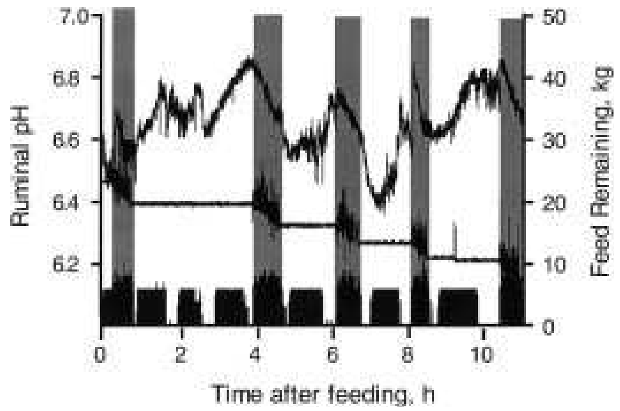

Figure 4. Continuous monitoring of a dairy cow feeding behavior and rumen pH show the clear decrease in rumen pH caused by ingestion of new feed. An increase in rumen pH during rumination is also clearly visible in response to salivary secretion, and absorption and passage of volatile fatty acids from the rumen. The top line represents rumen pH, the middle line the amount of feed left, and the bottom line the chewing activity. The vertical shaded bars indicate the meals (Allen, 1997).

Forage particle size affects feeding behavior and increasing particle size increases chewing time of cattle, which would, at least to some extent, increase saliva production and buffering effect in the rumen. The effects on rumen pH may however be limited, because other important factors also contribute to rumen pH regulation such as rate and extent of substrate fermentation in the rumen, and rate of absorption of acids produced in the rumen. Increasing the proportion of concentrate in the diet may also affect feeding behavior with very fast eating rates compared to forages. According to De Brabander et al. (1999), chewing time is not an ideal standard for describing physical structure of variable feeds. Tafaj et al. (2007) felt that the critical particle size of diet to stimulate chewing and rumination processes adequately may be smaller than often has been assumed.

Rumen pH

Dairy cows are at great risk of low ruminal pH, because of their high energy demand, and attempts to fulfill it by using highly digestible high concentrate diets for them. Other ruminant animal groups may also suffer from SARA, particularly if concentrate feed prices are low resulting in large quantities of easily fermentable carbohydrates in their diet. Chewing stimulates saliva production and increases the buffering capacity in the rumen. The role of excessive concentration of easily fermentable carbohydrates in the diet plays however a greater role in increasing the risk of SARA (Allen, 1997; Krause & Oetzel, 2006). If decreasing particle size increases feed intake, the total fermentable mass into the rumen and thus the production of acids thereof will increase and potentially cause a greater risk of rumen acidosis. With increasing DM intakes, a higher requirement for physical structure in the diet is needed due to greater production of fermentation acids.

The complicated interactions in dairy cow diet digestion were brought up by Krause and Oetzel (2006): Very long particle size of forages may also increase the risk of SARA by allowing the cows to select the more fermentable feed and leaving the fibrous long particles uneaten. Decreased selection against fiber with decreasing particle size was demonstrated in the experiments of Konoff et al. (2003) and Zebeli et al. (2009).

Allen (1997) concluded that although peNDF has an important role in stimulating saliva flow to neutralize fermentation acids, differences in rate and extent of organic matter fermented in the rumen seem to be the most important single factor affecting ruminal pH. Mertens (1997) showed a positive relationship between peNDF concentration and ruminal pH (Figure 5), but he also noted that peNDF and easily fermentable neutral detergent soluble fractions of feeds are negatively correlated. Although forage particle size may not be as important factor in causing SARA as the amount of easily fermentable carbohydrates fed, in a border-line situation it may be of importance.

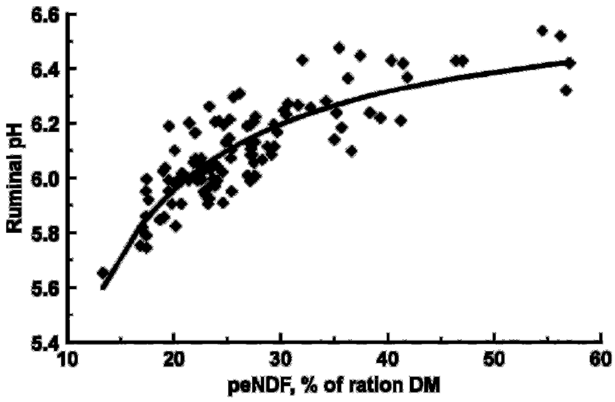

Figure 5. Mertens (1997) found a relationship between physically effective NDF concentration in the diet and ruminal pH.

A number of different background effects are likely to substantially modify the effects observed in individual experiments. In the data set of Tafaj et al. (2007), the effects of particle size were more profound on grass than on corn silage based diets. In a further analysis from the same group (Zebeli et al., 2008), on top of peNDF also ruminally degradable starch and DM intake affected ruminal pH, and the latest review (Zebeli et al., 2010) confirmed the important interactions between peNDF and ruminally digestible starch. Calculating the acidogenic value for the concentrate feeds could be used in ration formulation on top of peNDF to prevent SARA (Rustomo et al., 2006).

Forage NDF or peNDF concentration in the diet seems to be a better indicator of healthy rumen environment than total diet NDF concentration (Zebeli et al., 2008; Yang & Beauchemin, 2009). The results of Yang and Beachemin (2009) illustrate that increasing alfalfa silage particle size can only marginally reduce the risk of SARA while increasing the forage-to-concentrate ratio is more efficient (Figure 6). Further, Onetti et al. (2003) could not alleviate the negative effects of tallow supplementation in dairy cow diets by increasing the chop length of corn silage.

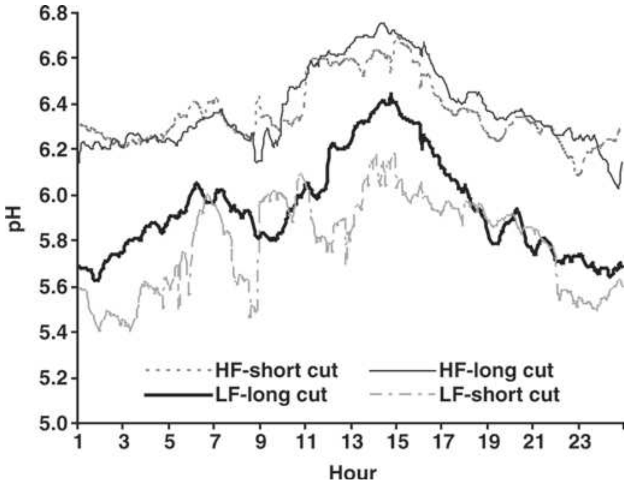

Figure 6. The ruminal pH measurements from Yang and Beauchemin (2009) demonstrate that diet fermentability (here manipulated by forage-to-concentrate ratio; HF = high forage and LF = low forage) has greater influence on ruminal pH than alfalfa silage particle size.

Grasses are more efficient than corn in maintaining stable rumen function as De Brabander et al. (1999) determined the critical values of roughage required in the diet to maintain normal rumen functions to be 205 g/kg for grasses and 348 g/kg for corn silages. This can be attributed to the higher fiber and lower easily fermentable carbohydrate concentrations in grasses compared to corn silage. Different types of grasses may also differ in physical effectiveness. Grasses typically have higher fiber concentration, but lower indigestible fiber (iNDF, determined as the residue after prolonged rumen incubation in nylon bag) concentration than forage legumes (Figure 7), and the high iNDF concentration of legumes might improve their structural value compared to grasses (Kuoppala et al., 2009). Further, the variation within forage types is also substantial. A 3-week delay in grass silage harvesting caused clear differences in NDF (486 *vs*. 654 g/kg DM) and iNDF (48 *vs*. 124 g/kg DM) concentrations, and in ruminal pH (5.99 *vs*. 6.29) of cows consuming similar concentrate allowance (Rinne et al., 2002). The role of iNDF in describing the physical effectiveness of ruminant feeds warrants further evaluation.

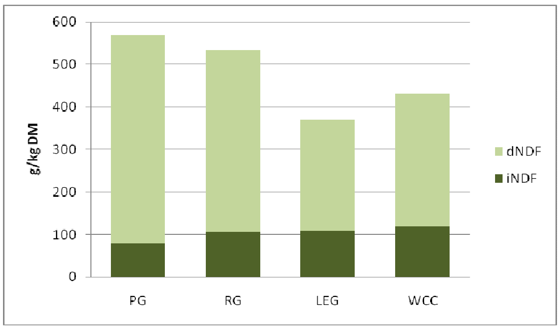

Figure 7. Primary growth grass (PG), regrowth grass (RG), legumes (LEG) and whole crop cereals (WCC) ensiled differ in the total fiber concentration [digestible NDF (dNDF) + indigestible NDF (iNDF)] as well as in the proportion of iNDF in total fiber (Huhtanen et al., 2006).

De Brabander et al. (1999) noted large differences in cows in the critical value of roughage needed in the diet to maintain normal rumen function. Thus relatively large safety margins are needed in practical diet formulation. Maybe with continuous technological development it will in future be possible to use individual rumen pH detectors placed in rumen of dairy cows also in practice, while the technology is currently available for experimentation (see e.g. Figures 4 and 6).

Digestion kinetics and fiber digestion

Rumen digestion is a dynamic process, where the digestibility of nutrients depends on the rate of digestion relative to the rate of passage (Allen & Mertens, 1988). Increasing passage rate and/or decreasing digestion rate will lead to decreased fiber digestion. Reduced particle size can decrease diet digestibility by increasing feed intake, which has been shown to decrease fiber digestibility (Huhtanen et al., 2009). Increased feed intake may further contribute to increased digesta passage rate, and decrease rumen pH, which both contribute to reduced fiber digestion. Tafaj et al. (2007) found a linear decrease in rumen pH and NDF digestibility with decreasing particle size (Figure 8).

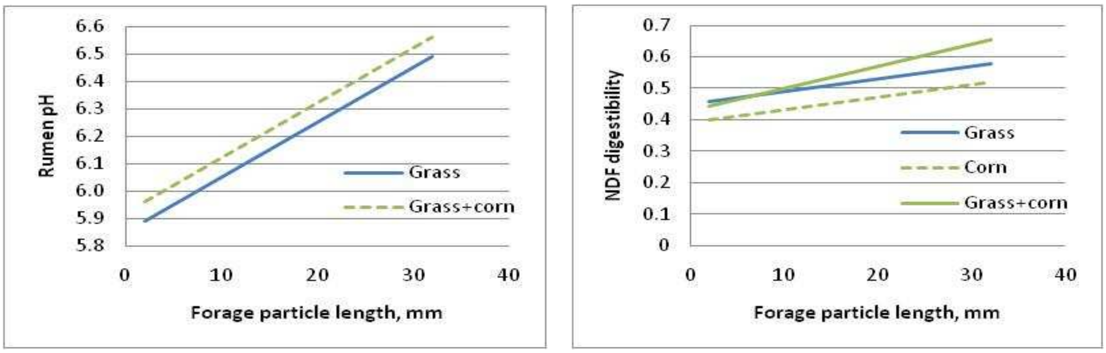

Figure 8. Increasing forage particle length linearly increased rumen pH and fiber digestibility in dairy cows (Tafaj et al., 2007).

Particle size has a role in determining the probability of particle escape from the rumen, but as majority of rumen particles is smaller than 1-2 mm, other factors such as specific gravity/buoyancy are also involved (Kennedy, 2005). Chewing and particularly ruminating contribute importantly to increasing the “escapability” of the forage particles by expelling the air pockets from feed particles.

The average particle size in the rumen is small compared to that in the diet. Differences in mean ruminal particle size have typically not been found when rations varying in forage particle size have been fed (Shaver et al., 1988; Tafaj et al., 2007). This indicates that the regulatory mechanisms of the ruminant on ruminal digesta particle size are more important than the particle size of the diet fed. In the meta-analysis of Tafaj et al. (2007), forage particle size did not affect ruminal passage rate and digesta mass suggesting that particle size reduction was not a rate-limiting step for particulate passage.

Fecal particle size can be used as a tool to measure the particle size of digesta leaving the rumen. Reducing the chop length of forage has increased the fecal particle size (Shaver et al., 1988; Teller et al., 1993; Rustas et al., 2010). Although this seems controversial, it may be explained by the reduced chewing time accompanied with reduced particle size of forage fed, and shows that the particle size decrease is more efficient when long *vs*. short chop forage is fed.

Effect of corn silage particle size on starch digestibility

When corn silage is prepared from a relatively mature crop with well developed cobs, grain processing is typically used to improve starch digestibility. Mertens and Ferreira (2005) described a method to analyze corn silage particle size with the aim to give an estimate of the kernel fragmentation and subsequent starch digestion.

Johnson et al. (2003) used macro nylon bags to incubate corn silages in the rumen of dairy cows to find out the effects of chop length and mechanical processing on the rate and extent of digestion in 5 experiments. There was some variability in the results, but mechanical processing improved DM and starch disappearance from the nylon bags more clearly than reducing chop length. Interactions were found so that the effects of mechanical processing were greater when corn silage was harvested at a later stage of maturity. Cooke and Bernard (2005) also found increased starch digestibility in dairy cows in response to more aggressive kernel processing, particularly when longer theoretical length of cut was used. Shorter chop length increased starch digestibility in barley silage harvested at dough-stage of maturity, but not earlier at heading-stage (Rustas et al., 2010).

Adding coarse forages to the rations

One method of increasing physical structure in dairy cow diets (typically TMR) is to add coarsely chopped high fiber hay or straw in small quantities into the recipe. This would improve rumen environment by stimulating chewing and saliva production, but also by substituting more fermentable components with less fermentable ones, and by decreasing feed intake.

Couderc et al. (2006) reported increased DM intake, when coarse chop corn silage was supplemented with long hay, but when fine chop corn silage was fed, DM intake decreased linearly in response to long hay addition. In many cases feed intake and subsequent production in beef cattle (Alende et al., 2009) and dairy cows (Ferris et al., 2000; Humphries et al., 2010) has decreased in response to addition of low quality forage in the diet. Adding coarse forage in the ration may be able to prevent clinical problems related to low rumen pH, and coarse forage additions can be used as “first aid” in such situations to maintain normal rumen function. In long term, other feeding strategies may however be more economically profitable.

Reducing forage particle size during preparation of TMR

The key points in the TMR quality from normal rumen function point of view are fiber concentration, particle size, and rate and extent of organic matter fermentation. They are mainly determined by the recipe of the TMR, and the qualities of the individual components. However, further processing of the diet also occurs at the time of TMR preparation in the mixer. The technical properties of the mixer and time of mixing will affect the final physical structure of the TMR produced. Humphries et al. (2010) reported smaller average particle size of vertical *vs*. horizontal mixer (11.7 *vs*. 14.2 mm) when identical ration components were used, and feed intake and milk production increased in cows consuming the smaller particle size diet.

Reduced feed selection is usually considered an important benefit of shorter chop length in TMR (Krause & Oetzel, 2006). Because cows usually select for the more digestible parts of the feed, reduced selection can be considered positive with regard to stable rumen function.

Conclusions

Based on the literature reviewed, the effects of forage particle size *per se* on both ensiling quality and rumen function are relatively small. Certain benefits from short particle size can be obtained in silage preservation, particularly when comparing ensiling technologies using precision-chopped *vs*. long grass, but good quality silage can also be obtained from long chop if good silage making practices are applied. Using diets with too low or too high physical structure will compromise the production of cattle, but it should be noted that too low physical structure will lead to animal health and welfare problems and decrease the longevity, while too high physical structure will decrease level of production without compromising animal health. The proportions of total fiber *vs*. easily fermentable carbohydrates in the diet may be more important than forage particle size when practical forage processing methods are used.

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