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Estimating silage energy value and milk yield to rank corn hybrids

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Abstract

This paper provides a revised summative energy equation and applies it to estimate the energy value of corn (*Zea mays*) silage. Estimating the energy value of corn silage is important, because energy is the primary nutrient contributed by corn silage to dairy cattle rations. Estimated energy intake from corn silage was used to estimate milk yield from corn silage by dairy cows. The milk yield estimate was used to rank corn hybrids in silage evaluation and breeding programs. The revised (MILK2000) forage quality (milk Mg^{-1}) and yield (milk ha^{-1}) indices were evaluated relative to MILK1995 indices in corn silage hybrid performance trials. A previously published summative energy equation (Weiss, 1996), with crude protein, fat, non-fiber carbohydrate (NFC), and neutral detergent fiber (NDF) fractions and corresponding digestibility coefficients, was adapted for corn silage as follows: the crude protein and fat fractions were not altered, the NFC fraction with constant digestibility was replaced with starch and non-starch NFC fractions, the starch digestibility coefficient was varied in relationship to whole-plant dry matter (DM) concentration and kernel processing, and the NDF digestibility coefficient based on lignin concentration was replaced by a 48 h or maintenance intake in vitro measurement of NDF digestibility (NDFD). Our summative approach integrates known differences in starch digestibility, as affected by whole-plant DM concentration and kernel processing, and NDFD into estimates of the energy value of corn silage. It also provides a framework for the future incorporation of laboratory measures of starch digestibility into estimates of the energy value of corn silage. For the MILK2000 model, we used our net energy for lactation estimates along with DM intake estimated from NDF concentration and NDFD to

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Abbreviations: ADF, acid detergent fiber; BW, body weight; CP, crude protein; DM, dry matter; DMI, dry matter intake; FA, fatty acids; IVTD, in vitro true digestibility; MILK2000, revised milk Mg^{-1} and milk ha^{-1} indices; MILK1995, original milk Mg^{-1} and milk ha^{-1} indices; N, nitrogen; NDF, neutral detergent fiber; NDFD, in vitro NDF digestibility; NE_L, net energy of lactation; NFC, non-fiber carbohydrate; NIRS, near infra-red reflectance spectroscopy

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estimate milk Mg^{-1} of corn silage DM. Corn hybrid checks characterized by high and low milk Mg^{-1} were selected on the basis of above average forage yield and either low or high NDF concentration. These low and high NDF check hybrids were then included in 61 trials conducted between 1995 and 2000. The frequency with which low NDF hybrids had greater estimated milk Mg^{-1} than high NDF hybrids was 0.90–0.93. Both maturity at harvest and NDFD strongly influenced the relative hybrid rankings with MILK2000 versus MILK1995. MILK2000 provides an index for evaluating relative performance among hybrids and could be applied to ranking hybrids tested in performance trials.

Keywords: Corn silage; Digestion; Energy; Neutral detergent fiber; Starch; Dairy cattle

1. Introduction

Corn (*Zea mays*) silage often comprises dietary storage, between 250 and 750 g kg^{-1}, for lactating dairy cows in the United States. Since energy is the primary contribution of corn silage to dairy cattle rations, its prediction is important for diet formulation, economic evaluation, and hybrid performance trials. The concentrations of crude protein (CP), fat, non-fiber carbohydrate (NFC), and neutral detergent fiber (NDF), and the digestibility of these nutrient components influence the energy value of feedstuffs (Weiss, 1994). Despite nutritionists' understanding of the factors affecting the energy value of feedstuffs, most equations used to predict the energy content of corn silage by commercial feed analysis laboratories are based solely on its acid detergent fiber (ADF) concentration (Chandler, 1990). This is a major shortcoming of current feed analysis systems for corn silage considering the recent advances in corn silage production that affect its energy value, such as high-oil (Drackley, 1997) and brown midrib-3 mutant (Oba and Allen, 1999) corn hybrids and kernel processing (Bal et al., 2000b).

When determined by difference calculation ($100 - \mathrm{CP} - \mathrm{NDF} - \mathrm{NDF}_{\mathrm{CP}} - \mathrm{fat} - \mathrm{ash}$), the NFC fraction of corn silage comprises starch, sugars, and fermentation acids. Weiss et al. (1992) used a constant digestibility coefficient for the NFC fraction. However, digestibility of starch is influenced by stage of maturity at harvest (Bal et al., 1997) and kernel processing with an on-board roller mill at harvest (Bal et al., 2000b). In vitro digestibility of NDF (NDFD) is greater for brown-midrib hybrids compared with conventional hybrids (Oba and Allen, 1999). To the extent that lignin is related to NDFD, the summative equation of Weiss et al. (1992) accounts for this difference between brown-midrib and conventional hybrids in their estimate of the energy value of corn silage. The dairy NRC (2001) suggests that NDFD measured after a 48 h incubation can be incorporated directly into their summative equation for estimating the energy value of feedstuffs. Undersander et al. (1993) presented a method for estimating milk Mg^{-1} of forage DM as an index of forage nutritive value based on the energy value predicted from ADF concentration and dry matter intake (DMI) predicted from NDF concentration. This index has been used in corn silage hybrid performance trials (Lauer et al., 1997). Undersander et al. (1993) did not take into consideration the digestibilities of starch and NDF in their equations. Analyses for corn silage starch and NDF concentrations and NDFD are available to the industry through commercial feed testing laboratories. Despite this fact, these analyses have not been used in an integrated fashion to estimate the nutritive value of corn silage. The primary objective of this paper was to revise a published summative energy equation and incorporate it into estimates of the energy value of corn silage and the potential of corn silage for milk yield by dairy cows. A secondary objective was to use revised milk Mg^{-1} and milk ha^{-1} indices to rank corn hybrids in performance trials.

2. Materials and methods

2.1. Energy equation and MILK2000 model

The most commonly used method of estimating the energy value of corn silage is through the use of empirical equations, where the net energy of lactation ($\mathrm{NE_L}$; $\mathrm{Mcal\,kg^{-1}}$) of corn silage is predicted by a statistical regression from its concentrations of ADF or NDF (Chandler, 1990). This approach relies heavily on the proportion of grain in whole-plant corn silage and its impact on whole-plant ADF or NDF concentrations, while ignoring NDFD and factors affecting starch digestibility.

The multi-component summative equation of Weiss (1996) estimates the $\mathrm{NE_L}$ value of feedstuffs based on the concentration and true digestibility of CP, fatty acids (FA), NFC, and NDF. Each nutrient fraction is multiplied by its respective digestibility coefficient to determine the amount of digestible nutrients contributed by each fraction, the digestible nutrient components are summed, and the total is corrected for the energy from metabolic fecal matter (Girard and Dupuis, 1988). This approach serves as the basis for feedstuff energy prediction in NRC (2001). We converted the resulting 1X-maintenance intake total digestible nutrients value to a 3X-maintenance intake $\mathrm{NE_L}$ value ($\mathrm{Mcal\,kg^{-1}}$) for lactating dairy cows according to NRC (1989). The complete Weiss (1996) equation with the conversion to a 3X-maintenance intake $\mathrm{NE_L}$ value is as follows:

$$\begin{aligned}\mathrm{NE_L}\ (\mathrm{Mcal\,kg^{-1}}) = {} & [(\text{digestible nutrients}_{\mathrm{CP}} + \text{digestible nutrients}_{\mathrm{FA}} \\ & + \text{digestible nutrients}_{\mathrm{NDF}} + \text{digestible nutrients}_{\mathrm{NFC}} - 7) \\ & \times 0.0245] - 0.12. \end{aligned} \tag{1}$$

This equation and its component equations were used as the basis for the multi-component summative equation that we developed. Our multi-component summative equation adapted the Weiss (1996) equation solely for corn silage. The CP and FA fractions were left the same as those used by Weiss (1996).

2.1.1. Digestible CP

Holter and Reid (1959) determined that the true digestibility of CP in fermented and unfermented silages and dry hays ranged from 0.9 to 1.0, with an average of 0.93. To estimate digestible CP the following equation was used by Weiss (1996):

$$\text{digestible nutrients}_{\mathrm{CP}}\ (\mathrm{g\,kg^{-1}}) = 0.93 \times \mathrm{CP\ g\,kg^{-1}}. \tag{2}$$

Heat-damaged protein was not included in our revised equation, because the CP concentration of corn silage is low and heat damage is normally low unless spoiling has occurred.

2.1.2. *Digestible fat*

The crude fat or ether extract fraction contains waxes and resins at variable concentrations and digestibilities within different forages. Fatty acids were estimated by subtracting one percentage unit from the percent fat (Weiss, 1996). A true digestion coefficient of 0.97 for FA was used (Weiss, 1996). Based on heats of combustion, fat contains 2.25 times more energy than carbohydrates (NRC, 2001). The complete equation for estimating digestible FA (NRC, 2001; Weiss, 1996) was as follows:

$$\text{digestible nutrients}_{\text{FA}}\ (\text{g kg}^{-1}) = (\text{g kg}^{-1}\ \text{fat} - 1) \times 0.97 \times 2.25. \tag{3}$$

2.1.3. *Digestible NFC*

Weiss (1996) used a true NFC digestibility of 0.98 for cows fed at a maintenance level of intake in the following equation for estimating digestible NFC:

$$\begin{aligned}&\text{digestible nutrients}_{\text{NFC}}\ (\text{g kg}^{-1})\\ &\quad = 0.98 \times (100 + \text{NDF}_{\text{CP}} + 1 - \text{CP} - \text{NDF} - \text{ash} - \text{FA}).\end{aligned} \tag{4}$$

We replaced the NFC fraction with starch and non-starch fractions, and digestibility coefficients were assigned to these fractions as follows.

2.1.4. *Digestible starch*

To determine digestible starch, the starch concentration of corn silage was multiplied by its starch digestibility:

$$\text{digestible nutrients}_{\text{starch}}\ (\text{g kg}^{-1}) = \text{starch g kg}^{-1} \times \text{starch digestibility}. \tag{5}$$

There are no laboratory procedures currently available to determine starch digestibility. We developed regression equations from data in the literature to predict total-tract starch digestibility from whole-plant dry matter (DM) concentration.

Bal et al. (1997) harvested whole-plant corn for silage using a conventional chopper at early dent (301 g kg^{-1} DM), one-quarter milkline (1/4 milkline, 324 g kg^{-1} DM), two-thirds milkline (2/3 milkline, 351 g kg^{-1} DM), and black layer (420 g kg^{-1} DM) stages of maturity and fed the treatment silages to 20 lactating dairy cows in a replicated 4 × 4 Latin square design. Diets contained 340 g kg^{-1} corn silage and 265 g kg^{-1} corn grain (DM basis). Apparent total-tract starch digestibilities of early dent, 1/4 milkline, 2/3 milkline, and black layer diets were 0.94, 0.93, 0.92, and 0.88, respectively. By partitioning the starch contributed to the respective diets by each corn silage, assuming a starch digestibility of 0.95 for the non-corn silage starch (Firkins et al., 2001), using individual cow starch digestibility data, and knowing the respective corn silage DM concentration, apparent total-tract corn silage starch digestibility was predicted from corn silage DM concentration. Predicted starch digestibility coefficients were adjusted to a maintenance level of intake using a 0.04 decline in digestibility per multiple of maintenance (NRC, 1989) with a maximum true starch digestibility of 0.98 (NRC, 2001; Weiss, 1996) for use in our summative equation.

In the trial of Rojas-Bourrillon et al. (1987), whole-plant corn silage containing approximately 400 g kg^{-1} DM was chopped at 0.95 cm theoretical length of cut and either processed with a roller mill or unprocessed prior to ensiling. Treatment silages were fed at 900 g kg^{-1} of diet DM to steers. Apparent total-tract starch digestion increased 0.05

($P < 0.01$) for processed versus unprocessed corn silage. Bal et al. (2000b) harvested whole-plant corn for silage (350 g kg^{-1} DM) at 0.95 cm theoretical length of cut without processing (control), and 0.95, 1.45, or 1.90 cm theoretical length of cut with processing using an on-board roller mill. Diets contained 340 g kg^{-1} corn silage and 280 g kg^{-1} shelled corn (DM basis). Processing increased ($P < 0.001$) dietary starch digestion in the total-tract 0.04 on average. Dhiman et al. (2000) harvested whole-plant corn for silage at 1/2 milk-line (384 g kg^{-1} DM) without or with processing using a stationary roller mill at the silo. Diets contained 340 g kg^{-1} corn silage and 270 g kg^{-1} high moisture ear corn (DM basis). Processing tended ($P = 0.09$) to increase apparent total-tract starch digestibility 0.04 over the unprocessed control. From these trials, we used reported total-tract dietary starch digestibilities, starch contents of the diets and respective corn silage, percentages of corn silage and corn grain in the diets, and assumed a 0.95 digestibility for the non-corn silage starch (Firkins et al., 2001) to calculate the effect of processing on the apparent total-tract digestibility in corn silage. Processing increased apparent total-tract corn silage starch digestion by about 0.05 in both Rojas-Bourrillon et al. (1987) and Bal et al. (2000a,b) and by 0.10 in Dhiman et al. (2000). Using the incremental increases in apparent total-tract starch digestibility caused by processing in these studies and the data of Bal et al. (1997), apparent total-tract starch digestibility was predicted from corn silage DM content. Predicted starch digestibility coefficients were adjusted to a maintenance level of intake using a 0.04 decline in digestibility per multiple of maintenance (NRC, 1989) with a maximum true starch digestibility of 0.98 (NRC, 2001; Weiss, 1996) for use in our summative equation.

Maximum apparent total-tract starch digestibility values for both processed and unprocessed corn silage were set at 0.95, while minimum starch digestibility values of 0.70 and 0.80 were set for unprocessed and processed corn silage, respectively, based on the review by Firkins et al. (2001) and because there were no digestibility values outside of this range included in the dataset used to derive the equations.

2.1.5. *Digestible non-starch NFC*

The concentration of non-starch NFC contained in corn silage was calculated by subtracting starch concentration from the concentration of NFC. Aside from the analytical error involved in the calculation of non-starch NFC, contained in this fraction are primarily sugars in unfermented whole-plant corn and primarily fermentation acids in corn silage. As an alternative to the difference calculation, sugars and fermentation acids could be determined analytically if a more accurate determination of the impact of fermentation quality on the energy value of corn silage was desired. A digestion coefficient of 0.98 was assigned to the non-starch NFC fraction (NRC, 2001; Weiss, 1996). Digestible non-starch NFC was calculated as follows:

$$\text{digestible nutrients}_{\text{non-starch NFC}}\ (\text{g kg}^{-1}) = 0.98 \times \text{non-starch NFC g kg}^{-1}. \tag{6}$$

2.1.6. *Digestible NDF*

The energy contributed by the NDF fraction in the Weiss (1996) equation was based on potentially digestible NDF as related to lignified surface area (Conrad et al., 1984). Since lignin is indigestible, it was subtracted from NDF to produce lignin-free NDF, and to correct for the inhibition of cellulose and hemicellulose digestion by lignin the proportion of NDF surface area covered by lignin was calculated (Weiss, 1996). A digestion coefficient of 0.75 was used for potentially digestible NDF. Weiss (1996) equation for estimating digestible NDF in forages was:

$$\text{digestible nutrients}_{\text{NDF}}\ (\text{g kg}^{-1}) = 0.75 \times (\text{NDF} - \text{lignin}) \times \left[1 - \left(\frac{\text{lignin}}{\text{NDF}}\right)^{0.667}\right]. \tag{7}$$

We used a maintenance intake or 48 h NDFD measurement (NRC, 2001) to replace the use of lignin as in the NDF sub-equation described in NRC (2001). The digestible NDF in our equation was calculated as follows:

$$\text{digestible nutrients}_{\text{NDF}}\ (\text{g kg}^{-1}) = (\text{g kg}^{-1}\ \text{NDF} \times \text{NDFD}). \tag{8}$$

2.1.7. *The complete multi-component summative equation*

To estimate the energy value of corn silage the contributions of digestible nutrients from CP, FA, starch, non-starch NFC, and NDF were summed and adjusted as previously described:

$$\begin{aligned}\text{NE}_{\text{L}}\ (\text{Mcal kg}^{-1}) = {} & [(\text{digestible nutrients}_{\text{CP}} + \text{digestible nutrients}_{\text{FA}} \\ & + \text{digestible nutrients}_{\text{starch}} + \text{digestible nutrients}_{\text{non-starch NFC}} \\ & + \text{digestible nutrients}_{\text{NDF}}) - 7) \times 0.0245] - 0.12.\end{aligned} \tag{9}$$

Undersander et al. (1993) presented a method for calculating milk Mg^{-1} of forage DM as an index of forage nutritive value (MILK1995). Their approach used a forage energy value predicted from ADF concentration (Rohweder et al., 1978; NE_{L}, $\text{Mcal kg}^{-1} = ((88.9 - (0.779 \times \text{ADF})) \times 0.0245) - 0.12$) and forage DMI predicted from NDF concentration (Mertens, 1987) in the calculation of milk Mg^{-1} of forage DM. For the MILK2000 model, we adapted the approach of Undersander et al. (1993) for corn silage using our equation to estimate the energy value and NDF concentration and NDFD to estimate DMI for the calculation of milk Mg^{-1} of corn silage DM.

Mertens (1987) determined that daily NDF intake per unit of body weight (BW) was approximately $12 \pm 1.0\ \text{g kg}^{-1}$. By multiplying this factor by BW, NDF intake (kg per day) was calculated. Dry matter intake (kg per day) was then calculated by dividing NDF intake (kg per day) by total dietary NDF concentration. Effects of fermentation quality or silage pH (Shaver et al., 1984) were not accounted for in the DMI equation. For our model, we used a 612 kg cow and $300\ \text{g kg}^{-1}$ dietary NDF concentration. We assumed that corn silage constitutes the entire forage intake and that forage NDF was $750\ \text{g kg}^{-1}$ of total NDF (NRC, 1989) to calculate corn silage NDF intake at $8.6\ \text{g kg}^{-1}$ of BW. Corn silage DMI (corn silage DMI_{base}). was determined by multiplying $8.6\ \text{g kg}^{-1}$ by 612 kg BW and dividing the result by the NDF concentration of corn silage.

Oba and Allen (1999) determined that a 0.01 change in NDFD was associated with a 0.17 kg per day increase in DMI. We assumed that the increase in total DMI was from corn silage DMI. To calculate the effect of NDFD on DMI the following equation was used:

$$\begin{aligned}&\text{corn silage DMI}_{\text{final}}\ (\text{kg per day})\\&\quad = [(\text{NDFD}_2 - \text{NDFD}_1) \times 17] + \text{corn silage DMI}_{\text{base}},\end{aligned} \tag{10}$$

where subscripts 1 and 2 represent the sample plot and trial average of all hybrids in the test for NDFD, respectively. The corn silage $\text{DMI}_{\text{final}}$ equals corn silage DMI_{base} when the sample and average NDFD are equal. By using the NE_L (Mcal kg^{-1}) estimate from our revised summative-energy equation and our corn silage DMI estimate, production of 35 g kg^{-1} fat milk from forage was estimated with the following equation:

$$35\,\text{g}\,\text{kg}^{-1}\ \text{milk (kg per day)} = \frac{A - B}{0.68}, \tag{11}$$

where A is the amount of energy supplied by corn silage, i.e. corn silage DMI (kg per day) × corn silage NE_L (Mcal kg^{-1}), and B is the cow's maintenance energy requirement (NRC, 1989) proportioned according to the concentration of corn silage in the diet, i.e. $0.08 \times \text{BW}\,(\text{kg}^{0.75}) \times \text{g}\,\text{kg}^{-1}$ dietary corn silage, and 0.68 is the factor to convert NE_L (Mcal kg^{-1}) to kg per day of 35 g kg^{-1} fat milk (NRC, 1989).

Milk Mg^{-1} of corn silage DM was calculated by dividing milk (kg per day) by corn silage DMI (kg per day) and then multiplying by 907.2 kg. Corn silage DM yield estimates were then used to calculate milk from corn silage ha^{-1} (Undersander et al., 1993).

2.2. *Hybrid performance trials*

Commercial seed companies submitted corn cultivars to be tested in the University of Wisconsin Corn Hybrid Evaluation program. The cultivars were divided into early- and late-maturity classes based on relative maturity and location.

The experimental design of each trial at each location was a randomized complete block with three replicates. Plots consisted of two rows 7.6 m long and 0.76 m apart. To reduce microclimatic and competitive influences from adjacent plots, cultivars were divided into early- and late-maturity trials. Trials were located near Arlington, Lancaster, Fond du Lac, Galesville, Valders, and Marshfield, WI. Plots were established by seeding at 90,000 seeds ha^{-1} and thinning to a constant target plant density of 79,100 plants ha^{-1}. Other management practices were similar to corn production practices of the surrounding area.

"High and low" quality corn hybrid checks were included in the trials. For trials conducted between 1995 and 1997, checks were selected on the basis of previous work conducted by the UW Corn Silage Consortium (Coors, unpublished). Between 1998 and 2000, new check hybrids were selected every year on the basis of above average DM yield and then sorted on the basis of NDF concentration. Low and high NDF concentration hybrids were evaluated for milk Mg^{-1} characteristics using MILK1995. A total of 61 trials contained hybrids with low and high NDF concentration check hybrids. The high and low quality checks were compared to the trial average. During 2000, five hybrids chosen for their range in maturity and forage quality components, were included as checks in five separate silage trials and were used to compare MILK2000 and MILK1995 results. The five hybrids were Dairyland Stealth 1297 (a low-NDF concentration short-season hybrid of intermediate silage yield), Pioneer 35R58 (a high-yielding grain hybrid of intermediate maturity), NK Brand 48V8 (a high-yielding leafy silage hybrid of intermediate maturity), Cargill F657 (a low-yielding, brown-midrib silage hybrid with high NDFD and intermediate to late maturity), and Pioneer 33A14 (a high-yielding, late-maturing grain hybrid). These hybrids were evaluated in five separate trials, each of which was planted at Madison and Arlington, WI. The design of each trial at each location was a randomized complete block with two (four trials) or three replications (one trial). Plots were single rows 6.1 m long and 0.76 m apart. Final planting densities were 75,400 plants ha^{-1}. For statistical analysis of hybrid treatments using PROC GLM (SAS Institute, 1995), trials were treated as random effects equivalent to blocks, replications within trials were treated as random effects, and hybrids were treated as fixed effects. Hybrid mean comparisons were made using least significant difference when F values were significant ($P < 0.05$).

At harvest, forage moisture and kernel milkline was assessed to provide an estimate of plant development (Wiersma et al., 1993). One row was mechanically harvested using a one-row, tractor mounted forage chopper (New Holland 707, New Holland, PA) and measured for yield. A 1 kg subsample was collected for moisture and quality measurements. Samples were ground to pass through a 1 mm screen.

The near infra-red reflectance spectroscopy (NIRS) broad-based prediction equations for determining forage composition were developed through evaluations of a large number of corn cultivars by the corn breeding project and the corn agronomy program in the University of Wisconsin Department of Agronomy during 1992, 1993, 1995, 1996, 1997 and 1998. Replicated forage trials were conducted at numerous locations throughout Wisconsin. Forage samples from each plot were collected at approximately 650 g kg^{-1} forage moisture. Forage samples and stover samples were collected from approximately 40 plants for each sample in each plot. Samples were oven dried at 60 °C for approximately 7 days, and then ground with a hammer mill to pass a 1 mm screen. Each year, all samples were scanned using a NIRS Systems 6500 near-infrared reflectance spectrophotometer (Marten et al., 1985). Using samples derived from the plots in the hybrid performance trials, standard NIRS procedures were used to select calibration sets for broad-based prediction equations for wet laboratory analyses (Martens and Naes, 1989; Shenk and Westerhaus, 1991; Shenk and Westerhaus, 1994). Samples (0.75 g) from each calibration set were analyzed for ADF, NDF, in vitro true digestibility (IVTD), and CP.

From 1992 to 1996, ground samples from each calibration set were analyzed for ADF, NDF, IVTD, and CP. Assays for ADF and NDF used 0.75 g samples and procedure A of Van Soest et al. (1991), excluding the use of alpha amylase and sodium sulfite. Acid detergent fiber and NDF were not adjusted for residual ash. Duplicate 0.25 g samples were used to determine IVTD. The 48 h fermentation was performed in centrifuge tubes (Marten and Barnes, 1980) with the inoculum enrichment method of Craig et al. (1984; Tilley and Terry, 1963), except that buffer and mineral solutions were as described by (Goering and Van Soest, 1970). After removal from the incubator, tubes were placed in a freezer. Undigested residue was subjected to the NDF procedure as described previously. Total nitrogen (N) was determined from 0.1 g samples using a Leco N analyzer (Leco Corp., St. Joseph, MI; Dumas method). Crude protein was calculated by multiplying total N (Bremner and Breintenbeck, 1983) by 6.25.

Laboratory procedures for ADF, NDF, and IVTD were modified slightly in 1997 and 1998 for bulk processing using the ANKOM system of fiber and digestibility analysis (Ankom Technology Corp., Fairport, NY). A 0.5 g sample was used for sequential detergent analysis of NDF, ADF, as well as IVTD. The NDF and ADF procedures used for the ANKOM analysis (Komarek et al., 1996) were modified to include a 120 min reflux and 4 min rinse with a 1.0 g kg^{-1} heat stable α-amylase solution (Mertens, 1991, Novo Nordisk Biochem North America, Inc., Franklinton, NC), followed by four additional 4 min. rinses. Buffer and mineral solutions for the NDFD assays remained the same as for 1992 to 1996. All compositional data were calculated on a DM basis.

The calibration sets from 1992, 1993, 1995, 1996, 1997 and 1998 were combined to provide a single broad-based calibration set for forage composition. From the data obtained in the laboratory, prediction equations were developed relating NIRS wavelengths to each of the quality variables (Shenk and Westerhaus, 1991; Shenk and Westerhaus, 1994). Criteria used to select equations were high coefficients of multiple determination and low standard errors of calibration and cross-validation. Modified partial least square (PLS) analyses were used to determine the wavelengths to include in calibrations (Martens and Naes, 1989). Statistics relating to NIRS prediction are provided in Table 1.

In vitro true digestibility and feed and residue NDF concentrations were used to calculate NDFD (Van Soest, 1982) by the following equation:

$$\mathrm{NDFD} = \frac{\mathrm{NDF} - (1000 \times (1 - \mathrm{IVTD}))}{\mathrm{NDF}}. \tag{12}$$

The calculated performance indices of milk Mg^{-1} (kg milk Mg^{-1} of corn forage) and milk ha^{-1} (kg milk ha^{-1} of corn forage) were used to compare cultivars (Undersander et al., 1993). Milk Mg^{-1} was predicted using the processed corn silage equation for starch digestibility described previously. Milk ha^{-1} is the product of milk Mg^{-1} and DM yield of whole-plant corn forage.

Table 1
Regression statistics for estimation of silage quality traits in corn determined by near infrared reflectance (NIR) spectroscopy

Trait	*n*	Mean	R^2	SEC	SEV(C)	Number of PLS terms	Math treatment
NDF (g kg^{-1})	581	455	0.93	13.6	14.7	12	1, 2, 2, 1
IVTD	571	0.78	0.93	0.13	0.14	12	1, 3, 3, 1
Protein (g kg^{-1})	578	76	0.95	2.5	2.7	12	1, 5, 5, 1
Starch (g kg^{-1})	101	282	0.95	16.1	20.1	8	1, 4, 4, 1

Global NIRS calibration set derived from samples collected from corn silage trials conducted in 1992, 1993, and 1995 to 1999 at multiple locations throughout Wisconsin. NDF: neutral detergent fiber; IVTD: in vitro true digestibility; R^2: coefficient of determination; SEC: standard error of calibration; SEV(C): standard error of cross-validation in modified partial least squares regression; number of PLS terms: number of terms used for modified partial least squares regression; math treatment: derivative order, gap, first smoothing, and second smoothing.

3. Results and discussion

3.1. Energy equation and MILK2000 model

Equations and predicted starch digestibility values for unprocessed and processed corn silage at varying DM concentrations are presented in Fig. 1. Starch digestibility for unprocessed corn silage was predicted with the following equation ($R^2 = 0.85$, $P < 0.0001$):

$$\text{starch digestibility}_{\text{unprocessed}} = 1.34 - (0.00135 \times \text{DM g kg}^{-1}). \tag{13}$$

Starch digestibility for processed corn silage was predicted with the following equation ($R^2 = 0.77$, $P < 0.001$):

$$\text{starch digestibility}_{\text{processed}} = 1.19 - (0.00081 \times \text{DM g kg}^{-1}). \tag{14}$$

Slopes of the unprocessed and processed corn silage starch digestibility regression equations indicate that DM content had a greater impact on the starch digestibility of unprocessed than processed corn silage. At 350 g kg^{-1} DM, predicted apparent total-tract starch digestibility for unprocessed and processed corn silage was 0.86 and 0.91, respectively. At lower DM concentrations the difference between processed and unprocessed silage was smaller and increased as DM concentration increased. This may be due to the starch in dryer kernels being less available for digestion (Philippeau and Michalet-Doreau, 1997). Johnson et al. (2000) reported that at advancing stages of maturity processing increased total-tract starch digestion to a greater extent than with less mature silages.

Corn silage NE_L and milk Mg^{-1} values estimated using empirical (Rohweder et al., 1978; Undersander et al., 1993; MILK1995) and multi-component summative (MILK2000)

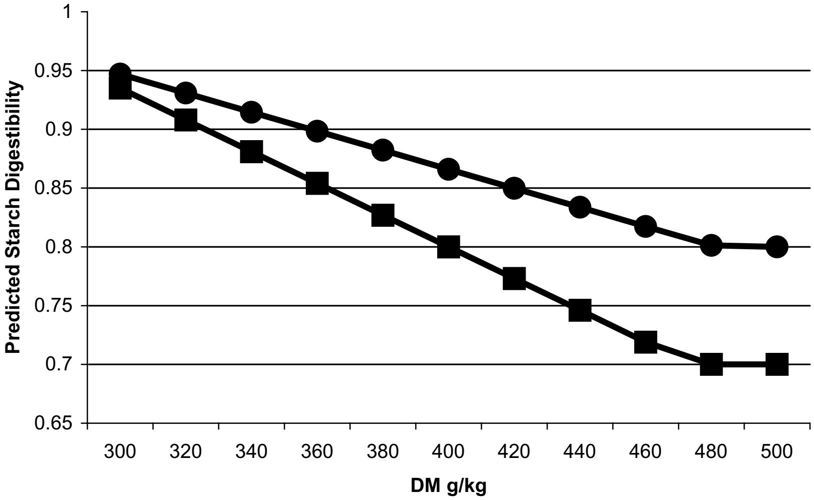

Fig. 1. Effect of corn silage dry matter concentration on predicted apparent total tract starch digestibility. Unprocessed corn silage (■), $Y = 1.34 - (0.00135x)$, $R^2 = 0.85$. Processed corn silage (●), $Y = 1.19 - (0.00081x)$, $R^2 = 0.77$.

Table 2
Estimated net energy of lactation and milk using empirical (Rohweder et al., 1978) and multi-component summative equations at varying whole-plant dry matter concentrations[a]

Dry matter ($g\,kg^{-1}$)	Empirical (Rohweder et al., 1972)[b]	Summative[c]	
		Processed	Unprocessed
Net energy of lactation (Mcal NE_L kg^{-1} corn silage dry matter)			
300	1.52	1.63	1.63
350	1.52	1.61	1.56
400	1.52	1.56	1.47
450	1.52	1.52	1.41
Milk (kg Mg^{-1} of corn silage dry matter[b,d])			
300	1615	1776	1776
350	1615	1744	1679
400	1615	1679	1550
450	1615	1615	1453

[a] Corn silage acid and neutral detergent fiber concentrations of 280 and 450 $g\,kg^{-1}$ (dry matter basis), respectively, were used across dry matter concentrations and equations.

[b] MILK1995.

[c] MILK2000.

[d] Undersander et al. (1993).

energy equations at varying whole-plant DM concentrations are presented in Table 2. For corn silage with 350 DM $g\,kg^{-1}$, the average NE_L estimate from our revised summative equation was 1.59 Mcal kg^{-1} DM. The Rohweder et al. (1972) empirical equation resulted in a constant NE_L value of 1.52 Mcal kg^{-1} DM across silage DM concentrations ranging from 300 to 450 $g\,kg^{-1}$. The estimated NE_L value from our summative equation was reduced from 1.63 to 1.41 Mcal kg^{-1} DM and 1.63 to 1.52 Mcal kg^{-1} DM for unprocessed and processed corn silage, respectively, as corn silage DM concentration increased from 300 to 450 $g\,kg^{-1}$ because of the effects of silage DM content and kernel processing on starch digestibility (Bal et al., 1997; Bal et al., 2000b). As found for NE_L, the milk Mg^{-1} estimates were constant across corn silage DM concentrations for MILK1995, but declined with increasing DM concentration for MILK2000. Decreases in milk production as corn silage DM content increases (Bal et al., 1997) and for unprocessed versus processed corn silage (Bal et al., 2000b) in feeding trials with dairy cows have been reported. Effects of fermentation quality or silage pH (Shaver et al., 1984) on DMI were not accounted for in our model, but DMI was unaffected by corn silage DM concentrations ranging from 300 to 420 $g\,kg^{-1}$ (Bal et al., 1997) and processing effects on DMI have been inconsistent (Bal et al., 2000b; Dhiman et al., 2000). Average milk Mg^{-1} estimates from MILK1995 were lower than from MILK2000, because in MILK1995 the cow's full maintenance energy requirement was subtracted from the amount of energy supplied by corn silage while in MILK2000 the cow's maintenance energy requirement was proportioned according to the concentration of corn silage in the diet.

A shortcoming of MILK2000 has been the lack of in vivo data for model validation (Shaver, 2002). Analysis of laboratory data (MILK2000 nutrient inputs to estimate corn silage NE_L value and DMI) and animal performance data (DMI, milk yield, and BW change) from nine corn silage treatment comparisons from four controlled experiments

(Satter et al., 2000; Schwab et al., 2002) and two commercial dairies showed an average predicted minus observed corn silage treatment difference of 0.64 kg milk per cow per day. An average predicted minus observed corn silage treatment difference of −1.3 kg milk per cow per day was observed using an ADF-based prediction (Schmid et al., 1976) of the corn silage NE_L value. Future testing of the MILK2000 model versus in vivo data is needed.

3.2. Hybrid performance trials

There were no significant DM yield differences between hybrids tested in 61 environments and selected for low and high NDF concentrations (Table 3). Maturity differences as measured by forage moisture content and kernel milkline were significant, but biologically small. As expected, fiber concentrations were lower for hybrids selected for low NDF concentration. In vitro true digestibility was greater for low NDF concentration hybrids. There were no differences in NDFD or CP concentration between low and high NDF concentration hybrids. MILK1995 indices were greater for low-NDF than high-NDF concentration check hybrids. Likewise using MILK2000, milk Mg^{-1} was greater for the low NDF concentration check hybrids. But, no difference was observed for milk ha^{-1} between low and high NDF concentration hybrids. In general, the "average" hybrid was intermediate in yield and quality measurements. Average milk Mg^{-1} and milk ha^{-1} estimates from MILK1995 were lower than from MILK2000 in Tables 3 and 4 and Fig. 2, because in MILK1995 the cow's full maintenance energy requirement was subtracted from the amount of energy supplied by corn silage while in MILK2000 the cow's maintenance energy requirement was proportioned according to the concentration of corn silage in the diet. This resulted in a consistent base change across samples that did not alter the cultivar comparisons or relative rankings within a model.

Ranking of check hybrids was consistent over the 61 trials. The corn hybrid checks were selected using the MILK1995 model. Using MILK1995 as an index to predict repeatability of hybrid performance in the 61 trials, we found that 0.74 ($P = 0.0002$) of the time the low NDF concentration hybrid would have greater milk Mg^{-1} than the high NDF concentration hybrid, and 0.90 ($P = 0.0001$) of the time the low NDF concentration hybrid would be either greater or be within ±1 standard deviation for milk Mg^{-1} of the high NDF concentration check hybrid. Using MILK2000, the low NDF concentration check hybrid would have numerically greater milk Mg^{-1} than the high NDF concentration check hybrid in 0.62 ($P = 0.05$) of the trials, and for 0.93 ($P = 0.0001$) of the trials the low NDF concentration hybrid produced either more or was within ±1 standard deviation for milk Mg^{-1} of the high NDF concentration check. Consistent relative performance is important for hybrid selection and ranking of a large number of hybrids tested in a trial.

Significant differences were observed for yield and quality of different hybrid types (Table 4). Significant changes in ranking occurred when comparing MILK1995 and MILK2000 (Fig. 2). The shorter-season hybrid (D1297) that was significantly drier was ranked significantly greater for milk Mg^{-1} and milk ha^{-1} using MILK1995, but using MILK2000 was only average for milk Mg^{-1} and below average for milk ha^{-1}. This was due largely to the negative impact of advanced maturity on starch digestibility in lactating dairy cows reported by Bal et al. (1997), being accounted for in MILK2000 but not

Table 3

Relative performance of corn hybrid checks pre-selected for low and high NDF concentrations tested in 61 Wisconsin environments conducted between 1995 and 2000 at six locations

Check	Dry matter yield (Mg^{-1} ha^{-1})	Forage moisture (g kg^{-1})	Kernel milk	Crude protein (g kg^{-1})	ADF (g kg^{-1})	NDF (g kg^{-1})	In vitro true digestibility (g kg^{-1})	NDF digestibility (g kg^{-1})	Starch (g kg^{-1})	MILK1995		MILK2000	
										Milk Mg^{-1} (kg Mg^{-1})	Milk ha^{-1} (kg ha^{-1})	Milk Mg^{-1} (kg Mg^{-1})	Milk ha^{-1} (kg ha^{-1})
Low NDF hybrid	17.1	610	0.44	73	224	444	784	516	320	2110	15800	3150	23900
Average hybrid	17.1	620	0.45	73	232	457	778	515	302	2020	15300	3110	23700
High NDF hybrid	17.4	617	0.50	73	237	465	774	515	295	1960	15000	3090	23800
L.S.D. (0.05)	NS	9	0.03	NS	4	6	4	NS	8	40	600	30	NS

Table 4
Relative performance of corn hybrids tested in five trials conducted during 2000 near Madison, WI

Hybrid	RM	Dry matter yield (Mg^{-1} ha^{-1})	Forage moisture ($\mathrm{g\,kg}^{-1}$)	Crude protein ($\mathrm{g\,kg}^{-1}$)	ADF ($\mathrm{g\,kg}^{-1}$)	NDF ($\mathrm{g\,kg}^{-1}$)	In vitro true digestibility ($\mathrm{g\,kg}^{-1}$)	NDF digestibility ($\mathrm{g\,kg}^{-1}$)	Starch ($\mathrm{g\,kg}^{-1}$)	MILK1995		MILK2000	
										Milk Mg^{-1} ($\mathrm{kg\,Mg}^{-1}$)	Milk ha^{-1} ($\mathrm{kg\,ha}^{-1}$)	Milk Mg^{-1} ($\mathrm{kg\,Mg}^{-1}$)	Milk ha^{-1} ($\mathrm{kg\,ha}^{-1}$)
Short-season (D1297)	98	14.8	543	72	248	493	724	440	294	776	11400	1360	20100
Mid-season (P35R58)	105	18.0	647	69	277	536	695	432	240	600	11000	1310	23800
Leafy (NK48V8/4687)	105	18.6	651	66	280	534	698	435	217	610	11400	1330	24800
Bmr (CF657)	110	12.7	687	74	254	504	744	491	263	808	10400	1520	19300
Full-season (P33A14)	113	17.6	700	72	297	553	682	425	211	525	9400	1260	22400
L.S.D. (0.05)		0.9	25	2	12	17	9	11	21	60	1300	40	1300
Mean		16.4	642	70	271	525	709	447	244	664	10800	1360	22100

D: Dairyland Stealth, P: Pioneer, NK: NK Brand, C: Cargill.

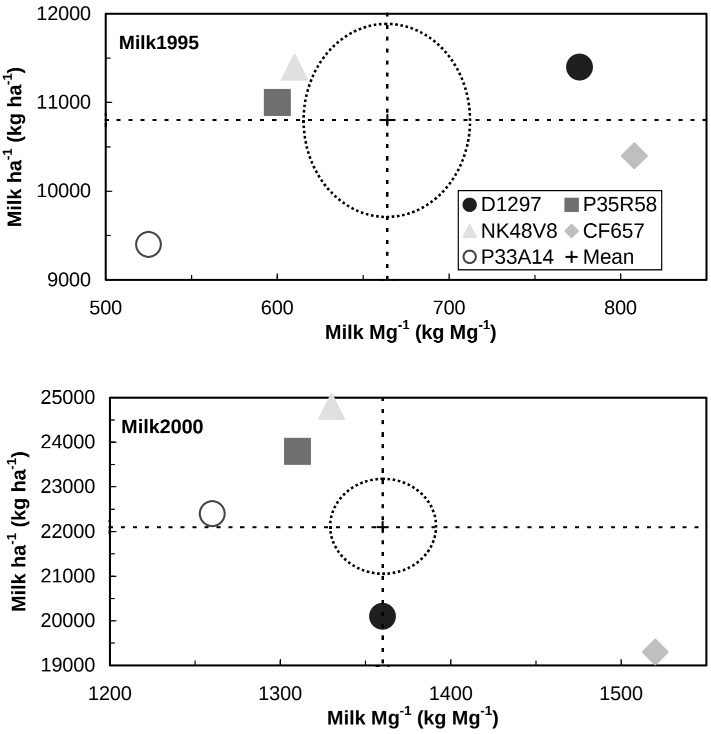

Fig. 2. Changes in milk Mg^{-1} and milk ha^{-1} between MILK1995 and MILK2000 of corn silage hybrids tested in five experiments during 2000 near Madison, WI. Dashed lines are the milk Mg^{-1} and milk ha^{-1} averages of the hybrids in the trials. Dashed ovals are ±1 S.D. for milk Mg^{-1} and milk ha^{-1} around the trial mean. D: Dairyland Stealth, P: Pioneer, NK: NK Brand, C: Cargill.

in MILK1995. Likewise, the relative ranking of the full-season hybrid (P33A14) was not affected for milk Mg^{-1} using MILK2000 versus MILK1995, but the ranking for milk ha^{-1} was higher because maturity was not as advanced for this hybrid. The brown midrib hybrid (CF657) was increased to a greater degree above the mean for milk Mg^{-1} with MILK2000 compared to MILK95, but had significantly lower milk ha^{-1} due to low yield. The increase in milk Mg^{-1} above the mean for the brown midrib hybrid with MILK2000 versus MILK1995 reflects its higher NDFD (refer to Table 4) being accounted for in MILK2000, but ignored in MILK1995. Increased milk yield for brown midrib hybrids in feeding trials with dairy cows has been reported by Oba and Allen (1999). Conversely to the brown midrib hybrids which were significantly higher than the mean of all hybrids for Mg^{-1}, leafy hybrids were similar to the mean. Similar milk yields for leafy and conventional hybrids in feeding trials with dairy cows have been reported by Bal et al. (2000a) and Kuehn et al. (1999). The leafy and mid-season hybrids (NK48V8 and P35R58) did not change appreciably in relative hybrid rankings for MILK2000 versus MILK1995. From these comparisons, it is apparent that maturity at harvest and NDFD strongly influence the relative hybrid rankings with MILK2000 versus MILK1995.

4. Conclusions

We have adapted two existing estimates of the nutritive value of forage, NE_L (NRC, 2001) and milk Mg^{-1} of forage DM (Undersander et al., 1993), for use in the evaluation of corn silage and the ranking of corn hybrids. Known effects of whole-plant corn silage DM concentration (Bal et al., 1997) and kernel processing (Bal et al., 2000b) on starch digestibility were incorporated into our NE_L estimate. Our summative approach provides a framework for future incorporation of laboratory estimates of starch digestibility, if and when they become available to the industry, into the NE_L estimate. Our approach also allows for the incorporation of known effects of corn silage NDFD (Oba and Allen, 1999) into the NE_L estimate and into the calculation of milk Mg^{-1} of corn silage DM from DMI and NE_L estimates. MILK2000 provides an index for evaluating relative performance among hybrids. This procedure is useful for corn breeders interested in developing silage hybrids, as well as extension agronomists and nutritionists interested in relative rankings of silage hybrids. In the United States, MILK2000 has been implemented in hybrid performance trials conducted by universities and commercial seed companies and is available through commercial feed testing laboratories. Future testing of the MILK2000 model versus in vivo data is needed.

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