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Towards smart dairy nutrition: Improving sustainability and economics of dairy production

Manfred Schönleben[1], Joachim Mentschel[2], Luboš Střelec[1]*

[1]*Department of Statistics and Operation Analysis, Faculty of Business and Economics, Mendel University, Brno, Czech Republic*
[2]*Department of Business Development, Sano – The Animal Nutritionists, Grafenwald, Loiching, Germany*

**Corresponding author: manfred.schoenleben@googlemail.com*

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Abstract: To satisfy increasing food and nutrient supply requirements for our growing future human population, farmers and staple food producers carry vital responsibilities. Especially farmers with ruminant livestock like dairy cows transform otherwise for human consumption unsuitable fibre into highly nutritious milk and meat. Nevertheless, dairy farmers are challenged increasingly by the consequences of global warming. Economic risks like feed supply and volatile commodity prices need to be balanced, also taking into account the increasing environmental awareness of end-customers. Focusing just on emissions, dairy production is contributing an essential part of the total carbon footprint emitted by the agricultural sector. Since rumen degradability of feed was identified by the Food and Agriculture Organization of the United Nations as one of the most influential parameters in reducing the carbon footprint of dairy farming, the desire to exploit leverage potential for efficiency increases can be considered exceptionally high. Although the positive effects of improved feed, in other words, neutral detergent fibre rumen degradability for dairy farming are well understood, detailed information on the correct management to obtain well digestible feed sources is still missing. Using the smart dairy nutrition ration formulation concept, applying readily on-farm available digitized data and management information the objectives of this study were: 1) to assess the influential parameters which govern neutral detergent fibre rumen degradability of corn silage, using a set of 584 corn silages from multiple years, and 2) to evaluate within an integrated dairy production set up the economic and ecological improvement potential by feeding a subset of 28 different corn silages, including detailed variety information. Results show that the neutral detergent fibre rumen degradability is primarily governed by variety choice and can be four times more important than the correct harvest stage decision. By feeding corn silage varieties with high neutral detergent fibre rumen degradability, monetary income could be increased by ~10% while simultaneously reducing manure accumulation.

Keywords: CNCPS; NDF rumen degradability; sustainable dairy farming; digitization; IOFC

To satisfy our growing appetite for high-quality nutrients and to support 9.8 billion fellow human beings, proposed to be living on the Earth in 2050, especially farmers carry key responsibilities (United Nations 2017). On the one hand, there is an increasing need for sustainable milk, meat and staple crop production, on the other hand, in the wake of global warming, increased ecologi-

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cal awareness of end-customers, politically driven environmental protection regulations, as well as volatile commodity prices and increased investment costs, dairy farmers are in urgent need to identify practical approaches to reduce unecological, unproductive nutrient emissions, as well as to increase their overall economic sustainability (FAO 2010). Currently, unpolluted air and a global healthy environment are from the microeconomic perspective, the willingness-to-pay (WTP) principle and customer view, non-economic goods (Roach et al. 2015).

Nonetheless, due to the fact that dairy production is contributing an essential part of the total carbon footprint and greenhouse gases emitted by the agricultural sector, the leverage potential of efficiency increases is perceived as exceptionally high (Gerber et al. 2011). Taking a closer look at the ecological efficiency of ruminants, especially dairy cows transform otherwise for human consumption unsuitable fibre into highly nutritious milk and meat. This includes fibre from marginal soils, unfit for efficient cropping and by-products from human food production like almond and soy hulls, beet and citrus pulp, as well as fermentation by-products (NRC 2001). As a linear polymer of up to ten thousand D-glucose units, cellulose is one of the main constituents of organic plant fibre and, in its abundance, unmatched on our planet (Russell 2002). The symbiotic relationship between ruminants and microbes allows for an efficient upcycling of these valuable feedstuffs and by-products, otherwise costly to dispose of or to combust (VandeHaar and St-Pierre 2006; Allen et al. 2018). From the greenhouse gas (GHG) efficiency perspective, milk delivers a more than twice as high nutrient density concerning GHG emissions, compared to soy drink (Smedman et al. 2010). Well understood are also the processes and links between nutrient use and excretion. Cornell Net Carbohydrate and Protein System (CNCPS) based diet formulation systems combine carbohydrate and protein degradation in feed and respective passage rates to simulate the extent of ruminal fermentation, microbial protein production, post-ruminal absorption, and total supply of metabolizable energy and protein to the animal (Van Amburgh et al. 2015). The CNCPS is a mathematical model that estimates nutrient supply and requirements of ruminants based on environmental, feed compositional, and animal information within diverse sets of production scenarios (Overton et al. 2010). Since about half of total milk production costs can be attributed to the fed diet, one key factor for economic and sustainable on-farm milk production is the income over feed cost (IOFC) (VandeHaar and St-Pierre 2006). The IOFC directly relates the dietary costs (investment into feed) with the realized monetary milk yield per cow to measure the economic income potential of a diet. Within CNCPS, diets can be optimized not only by the IOFC principle but also for agricultural externalities like excreted faeces, the core nutrients nitrogen (N), phosphorus (P), potassium (K) and the total carbon footprint (CO_2/NH_4) per litre of milk produced. Nonetheless, today's still widely used ration formulation systems for cattle, and dairy cows, with maximum security parameters for nutrient supply often lead to uneconomic nutrient emissions, unnecessary environmental pollution, suboptimal monetary incomes and often fail to comply with the ruminant's nutritional necessities (VandeHaar and St-Pierre 2006; Britt et al. 2018).

On dairy farms, nutrient efficiency and animal performance are strongly affected by the four factors: a) feed quality and quantity, b) ration formulation, c) ration delivery and supply, e.g. to avoid sorting, and d) farm management, including animal health (Hutjens 2018).

Essential for future sustainable dairy farming and animal welfare is, therefore, the application of state-of-the-art ration formulation solutions, efficiently using the on-farm available digitized data and management information. Within the smart dairy nutrition concept (SDN) via interfaces, CNCPS can take advantage of the vast and readily available digitized farm data from sources like milking parlour, herd management systems, and feed laboratory analyses (Masoero et al. 2007; Kaloxylos et al. 2012). Using SDN in combination with the economic IOFC concept, both the economic and ecological sustainability of dairy farming can be evaluated simultaneously.

The objectives of this study were: 1) to assess the influential parameters which govern NDF rumen degradability of corn silage, using a vast set of 584 corn silages from German dairy farms and multiple years, and 2) to evaluate within an integrated dairy production setup in Germany the economic and ecological potential of dairy production by feeding a subset of 28 different corn silage hybrids, analyzed using the CNCPS approach.

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MATERIAL AND METHODS

Rumen degradability of feed

From the cropping years 2017, 2018, and 2019 a set of 584 corn silages from different German farms were analyzed. Corn silage samples (800 g per sample) were collected, vacuum sealed, and sent to the Sano-CVAS laboratory in Popovaca/Croatia. Samples were air-dried at 60 °C for 24 h, ground, and subsequently analyzed *in vitro*, following CNCPS standard procedures via near-infrared reflectance spectroscopy (NIR) and proprietary Cumberland Valley Analytical Services (CVAS) European corn silage NIR-calibration. All subsequently measured corn silage and degradability traits were obtained based on the above-mentioned NIR analytics. Measured quality traits of corn silages included dry matter content in % (DM %), crude protein content in %DM (CP %DM), crude starch content in %DM (CS %DM), neutral detergent fibre content in %DM (NDF %DM), and lignin (lignin %DM). The NDF represents the respective amylase-treated fraction on an organic matter basis (aNDFom). Associated fibre rumen degradability traits included the neutral detergent fibre rumen degradability (NDFD30 in %NDF) after 30 h, neutral detergent fibre rumen degradability (NDFD120 in %NDF) after 120 h, and the indigestible neutral detergent fibre proportion (uNDF240 in %NDF) after 240 h.

Corn silage cropping regions spanned from southern Germany to the northern German coastline (47.683000°–53.551085° latitude, World Geodetic System), with cropping altitudes ranging from the sea level up to ~500 m above sea level.

From the current 2019 corn silage harvest, 28 early to mid-late corn varieties with known variety specifics and German silage FAO maturity information (Marton et al. 2007) were cropped together and separately ensiled in micro silos. The above-mentioned hybrid varieties represent a broad range of the elite corn silage germplasm currently commercially available in Germany, including early (FAO 210, n = 3; FAO 220, n = 4; FAO 230, n = 5), mid-early (FAO 240, n = 4; FAO 250, n = 9), and mid-late (FAO 260, n = 2; FAO 280, n = 1) maturity groups, from various breeding companies. Silage harvest maturity was determined by monitoring the kernel milkline, where harvest was conducted, when the hybrids reached their half milkline position (Wiersma et al. 1993). Subsampling of the hybrid-specific homogenized whole plant yield was conducted to gain three 1-kg samples which were stored in vacuum bags at 15 °C, respectively. Two months post ensiling, per hybrid, an 800-g silage subsample was collected, vacuum sealed, and sent to the Sano-CVAS laboratory in Popovaca/Croatia for further NIR based analysis of silage traits mentioned before.

NDF rumen degradability was modelled as neutral detergent fibre rumen degradability, after 30 h incubation in rumen fluid (NIR 30 h NDFd) in %NDF, using a linear mixed model approach, following:

$$y_{ijk} = m + g_i + a_j + d_k + (a \times d)_{jk} + e_{ijk} \qquad (1)$$

where:

y_{ijk} – 30 h NDFd for the ith variety, cropped in the jth year and harvested at kth maturity;
m – grand mean;
g_i – effect of the ith variety;
a_j – effect of the jth year;
d_k – effect of the kth harvest stage (maturity);
$(a \times d)_{jk}$ – interaction of the jth year and kth harvest stage;
e_{ijk} – error terms.

Factors variety (i), year (j), and harvest stage (k) were considered as fixed effects, the interaction between year and harvest stage (jk) was considered as a random effect. All phenotypic analyses were performed using R (R Core Team 2018) applying the lme4 package. Applied pairwise t-tests were Bonferroni corrected.

Economic and ecological sustainability

To obtain silage-specific IOFC and excretion results, laboratory analysis results from the 28 corn silage varieties cropped together were combined with a constant set of feeds, forming a diet fulfilling the requirements of the high lactating dairy cows, as reported in Table 1. Required animal biology, ecology, and management data for CNCPS dietary evaluation were obtained from a representative integrated dairy farm in Germany. Animal care and husbandry were conducted following the European Commission Directive 2010/63/EU on the protection of animals used for scientific purposes. Holistic evaluation of the diets was performed

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Table 1. Dietary composition and feed costs of total mixed ration for dairy cows to achieve the milk performance of ~37 l per cow and day

Dietary composition	Inclusion rate (kg on dry matter basis)	Inclusion rate (kg on as-fed basis)	Feed cost (€/t as fed)
Corn silage	11.00	34.00	55.0
Gras silage	1.75	5.00	49.0
Alfalfa hay	2.90	3.35	150.0
Distiller grains	0.13	0.5	30.0
Wheat grain grounded	3.75	4.2	170.0
Molasses	0.37	0.5	180.0
Soybean meal	3.40	3.8	380.0
Mipro RB 600 (Macro + microelements + vitamin premix)	0.60	0.60	750.0
Sum	23.90	51.95	–

hereinafter following the Smart Dairy Nutrition (SDN) concept by comprehensively linking on-farm digitized data sources, like herd management and monitoring systems, milking parlour, CNCPS feed analysis and dietary evaluation. The diet-specific IOFC was calculated as follows:

$$IOFC = \gamma \times \mu - \delta \quad (2)$$

where:

γ – milk yield in kg;

μ – milk price in €, adjusted for the fat (protein) premium, depending on the deviation from the base milk solids level;

δ – dietary costs in €.

To account for flexible milk component pricing, the milk price is commonly adjusted by the milk solids content within a bonus/malus context:

Milk price (€) = base price (at 3.8% fat and 3.4% crude protein) ± fat premium (cent/%deviation) ± protein premium (cent/%deviation) (3)

Required agricultural commodity prices were obtained following the board of trade information. Fat (crude protein) premium was evaluated with 5.0 cents (2.5 cents) per %deviation, using standard market information. Calculations of externalities (excretions) were conducted following the CNCPS (Fox et al. 2004).

RESULTS AND DISCUSSION

Identification of highly degradable feed sources

The analysis of the complete set of corn silages yielded a strong differentiation in the rumen degradability parameter 30 h NDFd in % of NDF (NDFD30) (Figure 1). The best linear unbiased estimators (BLUEs) basis is cropping season (2017), harvest dry matter (~31%), and NDFD30 (~62.5%), corresponding to a base of 62.5% of the NDF fraction digested in the rumen within 30 hours. BLUEs of variety effect on NDFD30 were dominant, followed by harvest stage (maturity) and finally cropping year. BLUEs of NDFD30 showed a range of 14% points (+3 to −11) for variety effect, a scale of 2% points (+2 to 0) for year effect and a range of 3.5% points (+2.5 to −1) for harvest stage (maturity). Considering the harvest stage, earlier maturities (harvests) yielded higher NDFD30 results.

In comparison with the harvest stage, the variety effect has a four-fold larger magnitude. This result suggests that the variety choice may be an effective tool for influencing the NDFD30 characteristics within the analyzed corn silages. One explanation for this observation may lie in the analyzed broad spectrum of modern European silage corn germplasm and maturity groups, with a potentially high level of differentiation of their cell wall architecture. The cell wall contains the NDF, which in turn includes the macromolecules of hemicellulose, cel-

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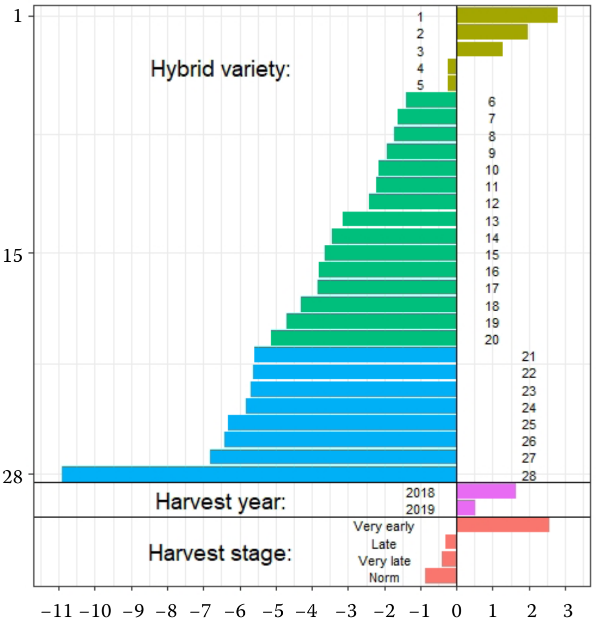

Figure 1. Effects on neutral detergent fibre (NDFD30) rumen degradability, depending on variety choice, harvest year and crop harvest stage (crop maturity). Basis (0) is cropping season 2017, harvest dry matter ~31% and NDFD30 ~62.5% (arithmetic average of the complete corn silage set)

lulose, and lignin (Van Soest et al. 1991). While the branched hemicellulose can be degraded more rapidly by rumen bacteria, slower degradability is attributed to the tube-shaped cellulose (Jung et al. 2012). Germplasm differences in NDF cellulose/hemicellulose proportions may therefore be partly responsible for the predominant differentiation of the analyzed germplasm.

Focusing on harvest maturity, differences in the lignification of the cell wall may be attributed a potent effect, since plant cells protected by a lignin layer are inaccessible for digestion by rumen bacteria (Wilson and Mertens 1995). While plant development controls the progressive lignification of the plant cell wall, varying plant cells and tissues differ in their level of lignification. For instance, a higher leaf to stem quotient, found in less mature corn silages, would quantitatively favour the harvest of less or non-lignified plant tissues and, consequently, NDF (Jung et al. 2012). Lignification may also bear principal responsibility for the detected main year effect. The harvest season 2018 was characterized by severe drought conditions in all German cropping regions and significant parts of Europe. In combination with earlier harvest decisions, the reduced plant development and consequently lignification of plant tissue may therefore be attributed to the positive deviation in NDFD30. The exceptional 2018 cropping season and corresponding dominating year effect on harvest decision and NDFD30 may also be responsible for the detected marginal importance of the interaction effect among harvest year and harvest maturity. This finding is unexpected, since interactions among main effects usually may not be neglected. Especially in polygenic scenarios, this is the rule, where an estimated large number of genes are involved in trait expression, like for plant cell wall formation and NDF composition (Jung et al. 2012). Within CNCPS based feed analysis and dietary formulation systems, in addition to the NDFD30 also the NDFD120 and the indigestible proportion of NDF, the so-called uNDF240, measured after 120 h and 240 h in rumen fluid are important quality parameters.

As a consequence, the subdivision into three rumen degradability pools (fast, slow, and apparently indigestible) yields high accordance between predicted and observed NDF ruminal degradation (Raffrenato et al. 2018). While NDFD30 (NDFD120) represents the fast (slow) degradable fibre pool, the uNDF240 pool represents the unavailable NDF proportion for nutrient extraction. Since the rumen volume is limited, a lower uNDF240 load in the rumen is correlated with higher feed intake and animal performance (Raffrenato et al. 2018).

The uNDF240, measured in % dry matter (DM), and NDFD30 show a high (−0.83) and highly significant ($P < 0.001$) Pearson correlation (Figure 2). Since the uNDF240 (in %DM) offers an improved perception of total digestible feed NDF within feedstuffs, the uNDF240 will be used subsequently in argumentations and descriptions.

Economic and ecological sustainability of dairy production

The analysis of the 28 corn silages with known detailed variety information cropped together yielded a strong differentiation of the rumen degradability parameter uNDF240 (Figure 3). Considering the total dry matter yield, the bulk nutrients from corn silage (36–45%) can be attrib-

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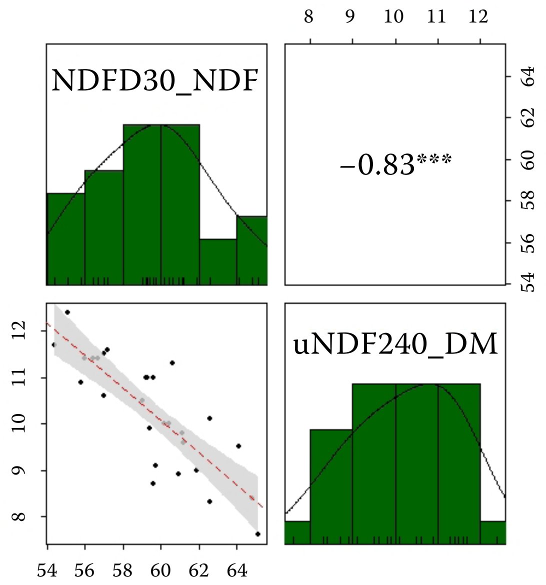

Figure 2. High (−0.83) and highly significant (***$P < 0.001$) Pearson correlation between the digestible neutral detergent fibre proportion (NDFD30 in %NDF after 30 h in rumen fluid) and the indigestible neutral detergent fibre proportion (uNDF240 in %DM, after 240 h in rumen fluid) using 28 corn silage hybrids from the cropping year September, 2019. The red dotted line shows the linear regression; the grey area covers the corresponding confidence interval

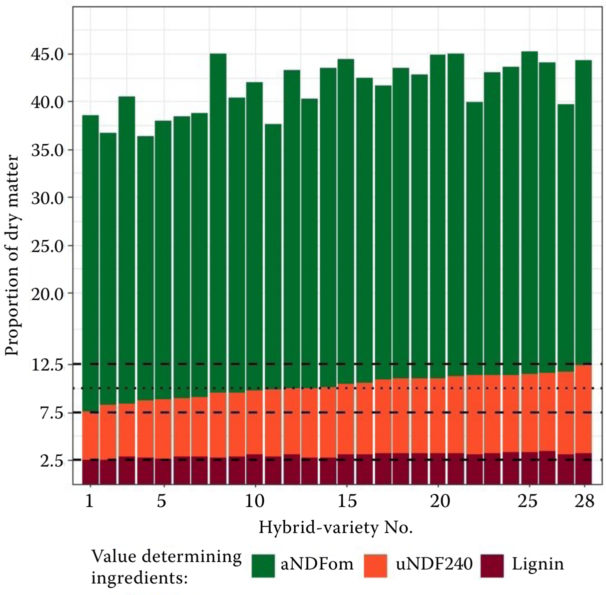

Figure 3. Value-determining properties of 28 corn silage hybrids (aNDFom: neutral detergent fibre, ash and amylase-adjusted; uNDF240: indigestible neutral detergent fibre after 240 h; lignin content) for the cropping year September, 2019

uted to NDF. The differentiation between the varieties concerning lignin content is low, with a mean value of ~2.5% total lignin content. Comparing the three hybrids characterized by a particularly high residual plant rumen degradability (hybrids 1–3: lowest uNDF240 contents) and the corresponding three hybrids with the lowest residual plant rumen degradability (hybrids 26–28: highest uNDF240 contents) the high digestible silages are characterized by an ~60% lower indigestible fibre load (uNDF240), ~10% higher NDFD30, as well as NDFD120 and NDFD240 results (NDF digestibilities after 30 h, 120 h, and 240 h) (Figures 3 and 4). The used animal welfare-oriented standard total mixed ration was constructed to fulfil the production requirements to produce ~37 litres of milk per cow and day (Table 1). Simulated feeding of the corn silage varieties within the CNCPS system yielded for the top three silage varieties (lowest uNDF240 contents) significantly higher ($P < 0.05$) IOFC results and significantly lower ($P < 0.001$) manure excretions (Figure 5, Table 2), compared to the poor three varieties (highest uNDF240 contents) (Figure 5).

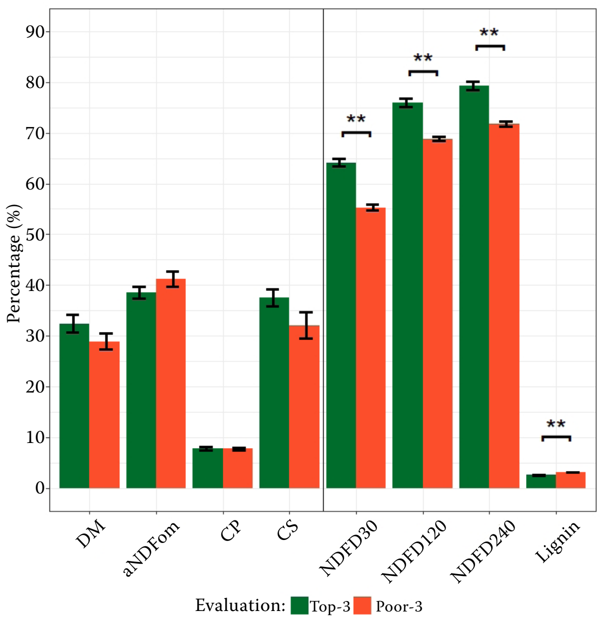

Figure 4. Comparison of value-determining properties of six corn silage hybrids, three with lowest and three with highest uNDF240 levels (indigestible NDF), harvest season September, 2019. The nutrient fraction contains dry matter (DM), NDF fraction (aNDFom, ash and amylase-adjusted), crude protein (CP), crude starch (CS), the NDF digestibilities after 30, 120 and 240 h, as well as the lignin content (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$)

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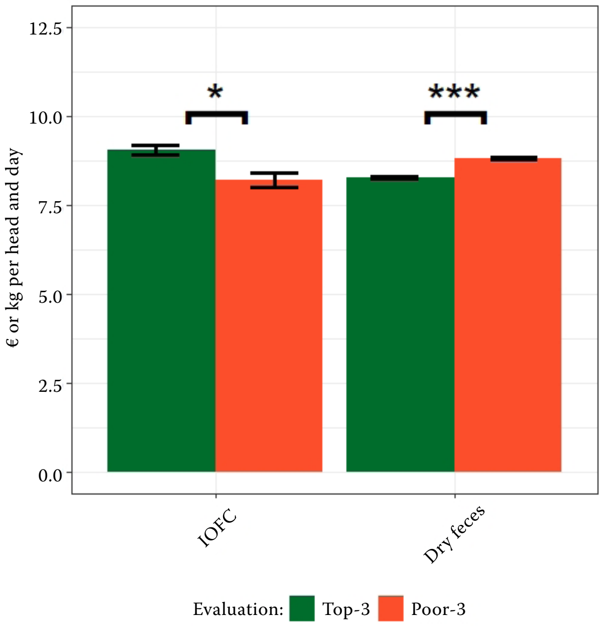

Figure 5. Economic (IOFC, € per head and day) and ecological (dry faeces excretion, kg per head, and day) results of feeding the corn silages with the highest (lowest) NDF rumen degradability (lowest and most top uNDF240 content) to high-producing lactating cows. The three highest/poorest digestible hybrids were selected, respectively (**P* < 0.05; ***P* < 0.01; ****P* < 0.001). Average milk production of top three (poor three) dairy cows at 39.1 kg (36.8 kg)/head and day with 3.8% fat and 3.4% crude protein milk solids content

From the absolute perspective feeding the corn silage varieties with the lowest uNDF240 yielded a 0.85 € higher IOFC per cow and day, feeding 11.0 kg of corn silage dry matter. Considering a dry matter content of corn silage of 31.5%, the diet includes ~35 kg of corn silage on an as fed basis. About 35 t corn silage yield per ha can be considered as a conservative estimate in central Europe. In this sense, from one ha of silage corn, a cow can be supplied with the discussed diet for ~1 000 days (or 1 000 diary cow day-rations). Converting the IOFC yield advantage per day to a yield advantage per ha, the IOFC advantage may be multiplied by the number of days the ration can be provided from one ha under *ceteris paribus* conditions following: 0.85 €/d × 1 000 d/ha = 850 €/ha.

In consequence, the correct management decision to obtain highly digestible corn silage can yield an improved income of 850 € per ha. This deviation is substantial, considering an average market service of 1 500 €/ha and year.

These results corroborate previous findings of studies performed in the United States, indicating German and European farmers may profit similarly from the merits of CNCPS based analytics and ration formulation (Oba and Allen 1999).

The NDF rumen degradability results for the broad range of modern German corn silage hybrids are suggestive of the value of the uNDF240 in identifying favourable and digestible corn silage varieties. Following the results, improved fibre rumen degradability as measured via uNDF240 can translate directly into a higher monetary income for the farmer, as well as in ecologically friendly reductions of externalities, like faeces or manure (Figure 5, Table 2). Identifying such highly digestible varieties may therefore not only be a more straightforward task but also, next to the agronomic potential, have a substantial impact within the global warming context (Allen et al. 2018). Furthermore, in the light of the proposed global increase in consumption of dairy products, future corn silage cultivars, improved for their cell wall rumen degradability, may contribute substantially towards more sustainable farming practices (Britt et al. 2018).

Especially ruminant livestock farmers and plant breeders may therefore profit from the uNDF240 (%NDF) assessment, since the comparatively broad

Table 2. Economic and ecological results of feeding the corn silages with the highest (lowest) uNDF contents to high-producing lactating cows. The three highest/poorest digestible hybrids were selected, respectively

Trait	Dry feces (kg)		Wet feces (kg)		Wet manure (kg)		IOFC (€)	
Group	Top-3: lowest uNDF	Poor-3: highest uNDF	Top-3: lowest uNDF	Poor-3: highest uNDF	Top-3: lowest uNDF	Poor-3: highest uNDF	Top-3: lowest uNDF	Poor-3: highest uNDF
Value	8.28	8.81	49.02	51.80	70.81	73.54	9.07	8.22
Difference	−0.53		−2.78		−2.73		0.85	
P-value	0.0005		0.025		0.029		0.032	

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differentiation between varieties simplifies a proper variety choice (Figure 1). Lignin content, on the other hand, may not be as suitable as the uNDF240. Although showing significant differences between varieties (Figure 4), the differentiation potential between varieties is weak (Figure 2).

CONCLUSION

The presented corn silage and feeding evaluations show the substantial economic and ecological effect of feeding forages with high fibre (NDF) rumen degradability and the impact of variety choice. On the other hand, the data attributes a rather minor importance to the harvest stage decision. This is good news for farmers and dairy managers, because the correct variety choice should not only yield high NDF rumen degradability, but also provide a larger harvest window. Since from the economic perspective today, up to 50% of total milk production costs can be attributed to the fed diet, these facts put a strong flashlight on core nutrients for dairy farms like the NDF. In this sense, rumen degradable NDF can be seen as the new "green gold" of dairy farming, and identifying and producing highly degradable feed NDF should therefore be a prime concern to farmers and dairy managers. Especially for the management and identification of highly degradable NDF, the CNCPS model and analysis may be well-suited standard procedures. The selection of well degradable feed NDF sources and varieties for planting may therefore be based on the uNDF240 due to its promising differentiation potential. To further substantiate these results and to better identify potential interaction effects among genotype, cropping season and harvest stage, we encourage to expand the CNCPS silage analysis to a more significant number of corn silage varieties and harvest situations. These future results may supply valuable additional information for tailored and regional specific corn silage cropping strategies to optimize rumen degradable NDF yields.

Since present-day still widely used standard ration formulation systems for ruminants do not support the combination of farm-specific digitized data, as well as economic and ecologic perspectives, dairy professionals may profit from modern digitized solutions and dietary evaluation systems like the CNCPS to avoid uneconomic overfeeding and nutrient emissions. For instance, using the smart dairy nutrition (SDN) concept, via interfaces, CNCPS can take advantage of the vast and readily available farm data from sources like milking parlour, herd management systems and feed laboratory analyses. The feeding results show that economic and ecological sustainability can be improved simultaneously. By supplying the corn silage varieties with high NDF rumen degradability, IOFC could be increased by ~10% while simultaneously the manure accumulation could be reduced. These results are very encouraging and good news for the environment, end-customers and dairy farmers alike, in the combined quest to simultaneously improve the economic and ecological sustainability of dairy production.

Conflict of interest

The authors declare no conflict of interest.

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