2000 Pacific Northwest Nutrition Conference

HIGH ENERGY BY-PRODUCTS IN BARLEY-BASED FEEDLOT DIETS

Mark Nelson
Department of Animal Sciences
Washington State University

Barley, fed to ruminants, has three characteristics that limit its usefulness. First, barley has a very rapid rate of ruminal starch fermentation which increases acidosis and decreases feed intake. Second, barley's high fiber content is rather extensively fermented causing cattle feeders to add substantial forage to the diet instead of balancing for total fiber. This reduces efficiency. Last, due to the large amount of barley starch and fiber that is ruminally fermented, large amounts of methane are generated reducing the barley's metabolizable and net energy content.

Methane is an important energy loss to ruminants, ranging from 2 to 12% of gross energy (GE). Typically, ruminants fed high grain diets lose 2-4% of GE as methane. However, sheep fed barley diets in my laboratory lost up to 6% of GE intake as methane in one study (Ovenell-Roy et al., 1998c) and 8% in another (Criswell et al., 1996). Barley is the major feed grain in the Northwestern United States and Canada, therefore, this is a substantial loss of energy and efficiency for the industry. Substitution of potato process residue for barley is rather common but reports on its feeding value are variable due to its variable composition and fat content.

Typically, finishing diet formulations in the Southwestern United States contain 3-6% supplemental fat primarily to increase energy density of the diet, reduce heat increment and thereby improve feed efficiency. Some cattle feeders in the Northwestern United States and Canada currently add dietary fat from tallow but also oils retained in cooked potato process residue including French fries and hash brown potatoes. The objective of this review was to discuss the current understanding of the feeding value of potato process residue and fat in barley-based finishing diets.

Potato Process Residue

There are four main types of potato by-products available. The names vary among potato processors and some processors combine the types into one product (commonly called slurry). The four types are potato peels, hopper box (small potatoes and pieces), cooked product (fries, hashbrowns, crowns, batter, crumbles, and small quantities of residues from water recovery systems (oxidation ditch or belt solids) which are mostly microbial cells and solubles. Chemical composition varies depending on what combinations of by-products are in it (Table 1). Dry matter contents typically vary from 12 to 30%. Potato peels or pieces have a chemical analysis similar to barley except for higher ash in the peels. Peels from the UK, however, had low ash content. Note that potato slurry has varied in CP and had high ash contents when processors used lye to peel the potatoes. All potato by-products are low in EE except for cooked products. The analysis of Rooke et al. (1996) is typical. For example, I analyzed the production from one plant for one week in 1992 and found EE to vary from 10 to 35% and type of cooking oil varied from tallow to various oils. Therefore, not only EE but also fatty acid composition varied dramatically. Currently, most processors are using partially hydrogenated oils so degree of unsaturation shouldn't vary as much.

Heinemann and Dyer (1972) fed graded levels of potato slurry (0 to 52% to finishing steers and concluded feed intake, gain, feed efficiency and dressing percent were not affected until 52% potato slurry was fed (Table 2). Carcasses from the two middle levels of potato slurry averaged Choice$^+$ and those from the other three treatments averaged Choice$^-$. Additionally, they measured DE and calculated ME content of the potato slurry at 19.2% (3.5 and 3.3 Mcal/kg, respectively) and 37.5% of DM (3.1 and 2.9 Mcal/kg, respectively). A contemporary study (Dickey et al., 1971) measured 2.0 Mcal ME/kg with sheep. Barley, Pacific Coast had a tabled value of 2.9 Mcal ME/kg.

Heinemann et al. (1978b) replaced a barley-beet pulp mixture with 26.6% potato slurry. They concluded that potato slurry-fed steers ate more (9.2 vs 8.4 kg/d), gain more (1.2 vs 1.0 kg/d), were more efficient (8 vs 8.5) and marbled more (Modest- vs Small+) than steers not fed potato slurry. This was most likely the result of positive associative effects. These early studies suggested that the energy value of the potato slurry was at least similar but could be greater than that of barley.

I (M. L. Nelson, unpublished data) fed 371 kg large frame steers for 152 d diets of potato peels at 10 or 20% with either 0, 7.5 or 15% forage (alfalfa hay, corn silage). Dry matter intake linearly decreased ($P < .05$) from 12.4 to 11.4 kg/d suggesting palatability problems or energy density changes. Average daily was quadratically affected ($P < .05$) where gain was maximized at 10% potato peels (1.5 vs 1.4 kg/d). Therefore, feed efficiency was quadratically affected ($P < .05$) by being minimized at 10% potato peels. There were no effects on carcass characteristics averaging 72% Choice and Small 30 marbling. These data show 42% and 21% more energy in potato peels than the barley it replaced. We (Duncan et al., 1991) concluded that potato peels altered the in vitro rate of disappearance (Table 3) of insoluble DM which contributed to altered energy content of potato peels.

Nelson et al. (2000) fed 10 or 20% hopper box by-product to finishing steers and concluded that NE_m and NE_g content was the same as barley (2.2 and 1.5 Mcal/kg, respectively) at 10% of DM but was 5% lower than barley at 20% of DM. Further, no biologically important impacts on quality or palatability of the beef were detected (Nelson et al., 2000; Busboom et al., 2000). Rooke et al. (1997) measured ME content of potato peels and French fries with sheep to be 2.8 and 3.09 Mcal ME/kg. Using the Garrett (1980) equation, peels contained 1.8 and 1.2 Mcal NE_g/kg, respectively. These data show the impact of type of potato by-product and cooking on energy value relative to our modern higher energy containing barley varieties.

Fats

The impact of fats and oils in cooked potato products lead us to study their impacts in barley-based finishing diets. It is not the goal of this paper to completely review this topic, but to discuss alternative hypotheses in order to help elucidate when supplemental fats would be beneficial. For example, NE_m and NE_g content of yellow grease has been reported to be 6.2 and 4.5, respectively (Zinn, 1988), 6.0 and 4.8, respectively (Zinn, 1989) and 5.7 and 5.0 Mcal/kg, respectively (M. L. Nelson, unpublished data). Clearly, interactions of fat with diet components, ruminal fermentation, and postruminal digestion affect the energy value of supplemental fat.

Energy lost as methane varies from 2 to 12% of dietary gross energy intake in ruminants (Czerkawski, 1988), with most high grain diets losing 2 to 4%. However, we (Ovenell-Roy, et al., 1998c) recently directly measured methane losses up to 7% of GE in wethers fed barley diets. Stoichiometrically, high grain diets yield an acetate-to-propionate ratio of about 1:1 which theoretically yields 1 mole of methane and high forage diets yield a 3:1 acetate-to-propionate ratio and 3 moles of methane. Our (Ovenell-Roy et al., 1998a,b) measurements of acetate-to-propionate in barley-fed steers were from 1.2 to 1.6:1.

Methanogenic microorganisms are greatly affected by diet. It is well documented that increased rate of passage or digestion or decreased pH results in less methane produced, all probably by increased propionate and less acetate production but also through reduced protozoa which are very active in hydrogenation of unsaturated fatty acids. Barley has a rapid rate of fermentation which decreases ruminal pH but it also contains substantial fiber. Barley fiber is also rapidly fermented in comparison to other grain. We measured fermentation of barley fiber polymers to vary from 62 to 78% among specific polymers (Ovenell-Roy et al., 1998a,b). More importantly, neutral detergent fiber (NDF) digestibility varied up to 15 percentage units among barley cultivars and NDF and/or polymeric monosaccharide digestion was correlated with methane emitted (Ovenell-Roy et al., 1998b).

Supplemental fat (> 6% of DM) decreases fiber digestion (Palmquist and Jenkins, 1980) and methane production *in vitro* (Czerkawski, 1973). The four hypotheses suggested by Devendra and Lewis (1974) for how dietary polyunsaturated fatty acids alter ruminal fiber fermentation were: (1) physical coating of the fibers by oil; (2) shortage of calcium due to formation of insoluble soaps; (3) inhibition of rumen microbial activity; (4) modification of microbial population by intoxication. Additionally, hydrogenation of fatty acids is less complete when ruminants are fed high grain rather than high forage diets (Latham et al., 1972) or when free fatty acids, not triglycerides, were provided (Palmquist and Jenkins, 1980).

A balance trial was conducted to titrate the effects of tallow on energy metabolism of wethers fed barley-based finishing diets (Criswell et al., 1996, Nelson et al., 1998). Diets contained 73% barley, 0, 2, 4 6, 8, or 10% tallow and/or bentonite, 10% alfalfa and 7% supplement. Level of tallow did not affect OM intake (1.1 ± .04 kg/d) or diet digestibility of OM (83.7 ± .83%), starch (99.6 ± .05%), N (73.4 ± 1.51%) and gross energy (83.1 ± 1.03%). However, protozoal numbers (mostly *Entodinium spp.*) decreased linearly ($P < .05$) from 8.5 to 2.1 x 10^5 mL as did solubility of barley ($P < .10$), by almost twice the tallow amount, and in situ rate and disappearance of insoluble DM ($P < .10$). The polymeric monosaccharides xylose, galactose, glucose digestibility decreased linearly ($P < .05$) as tallow increased.

Diet gross energy and digestible energy increased linearly ($P < .05$) from 4.6 to 5.1 Mcal/kg OM and from 3.8 to 4.2 Mcal/kg OM, respectively. Methane emission decreased quadratically ($P < .01$) from 41 L/d (0% tallow; 38.3% GE) to 18.3 L/d (10% tallow; 3.2% of GE) with a minimum of 14 L/d at 6% tallow. Diet ME increased linearly

from 3.4 to 4.0 Mcal/kg OM. The barley contained 4.1 and 3.5 Mcal/kg OM and the tallow on average contained 8.2 and 4.7 Mcal/kg OM of DE and ME, respectively, even through fatty acid digestibility was substantial.

Electron micrographs apparently showed not only a fat layer on fibrous components and starch granules of the barley kernel but also reduced disappearance of both the fibrous components and the endosperm, probably due to fatty acids preventing microbial attachment to feed particles or of bacterial cellulases to cellulose as suggested by Immig et al. (1991). Protozoal numbers (mostly *Entodinium spp.*) linearly decreased ($P < .05$) as level of dietary tallow increased clearly showing intoxication of ruminal microbes. Ikwuegbu and Sutton (1982) noted protozoal elimination and an increase in total bacterial numbers due to level of linseed oil fed to sheep. Broudiscou et al. (1994) reported that 6% linseed oil in a 45% concentrate diet of sheep decreased ($P < .01$) protozoal numbers from 5.6 to 1.9 X 10^3/ml and reduced ruminal hemicellulose digestion. However, as noted by Sutton et al. (1983), fermentation in the hind gut can compensate for lower ruminal hemicellulose fermentation due to dietary linseed oil. A shortage of calcium was unlikely in the current study due to the amount of dietary Ca (.6%) exceeding the amount needed to form soaps with all fatty acids. Therefore, physical coating, even though evidence exists that fat does not coat fiber particles (Ørskov et al., 1978; Mir, 1988; Drackley, et al., 1994) appears important. It might be logical to expect minimal effects on fiber fermentation if bacterial numbers increase due to less predation by protozoase inhibition of microbial activity and intoxication of protozoa appear important as well.

Effects of supplemental fats on ruminal fermentation have been reported that include decreased fiber fermentation (Kowalczyk et al., 1977; Criswell et al., 1996), decreased ruminal microbial populations, especially protozoa (Broudiscou et al., 1990; Jenkins, 1993; Criswell et al., 1996), and decreased methane emission (Criswell et al., 1996; Czerkawski et al., 1996). While these results are well documented, satisfactory theories or relationships among these phenomena have not existed until now.

A widely accepted theory was that ruminal hydrogenation of unsaturated fatty acid served as a hydrogen sink and, thereby, reduced methane emission. When hydrogen balance was calculated, the observed decrease in methane in Criswell et al. (1996) was much greater than the hydrogen sink potential. This indicated that unsaturated fatty acid affect methanogenesis by other mechanisms.

Wedam (1999) showed that methanogens associated with ruminal protozoa were not ectosymbionts, as was widely accepted (Imai and Ogimoto, 1978; Yokoyama and Johnson, 1988; Van Soest, 1994), but were endosymbionts. We (Wedam et al., 1999) developed a microscopy technique based on autofluorescence of an enzyme (F_{420}), which is a reduction enzyme in the methanogenesis pathway, and applied it to ruminal protozoa. Others have confirmed by mRNA hybridization that endosymbionts in protozoa from landfills, ponds and marine sand are methanogenic bacteria belonging to the kingdom Archaea (Embley et al., 1992a,b). Wedam (1999) also used transmission electron microscopy on cultured ruminal protozoa to confirm these endosymbionts were living within the cytoplasm not being digested in food vacuoles.

Ruminal protozoa have hydrogenosome organelles that produce hydrogen and carbon dioxide which methanogens utilize to produce ATP by methanogenesis. Wedam (1999) showed that endosymbiotic methanogens were concentrated in areas with large numbers of vacuoles and hydrogenosomes. Hydrogenosomes have been described in non-ruminal protozoa as anaerobic versions of mitochondria (Benchimol et al., 1982; Benchimol and de Souza, 1983; Finlay and Fenchel, 1989).

Wedam (1999) attempted to quantify the relationships between ruminal protozoa, their endosymbionts, methanogens and methane emission by perturbing ruminal fermentation in cows fed alfalfa with supplemental fat. However, in this study and in others (Smith et al., 1993; Wu et al., 1993) dietary tallow was rendered inert possibly by physical adherence or formation of calcium soaps (Jenkins, 1993).

Since ruminal protozoa and methanogenesis are sensitive to dietary tallow addition with barley-based diets (Criswell et al., 1996) but not with alfalfa-diets (Wedam, 1999) and ruminal methanogens and methanogenesis are sensitive to unsaturated fats (Dong et al. 1997), we developed an alternative theory. We proposed that specific fatty acids are toxic to methanogenic bacteria (Hendersen, 1973) which are endosymbionts. The loss of the endosymbionts results in either reduced competitive advantage or protozoal death. Supporting our theory are results of Fencel and Finley (1991) who showed a 30 to 40% decrease in growth of a non-ruminal protozoal by chemical removal of endosymbionts. Therefore, we measured the toxic effects of specific fatty acids (C18:0, C18:1, C18:2 and C18:3) on the protozoal population and their endosymbionts (M. Ney, J. Schmidt, and M. L. Nelson, unpublished data).

Rate of gas accumulation with the barley substrate was greater ($P < .10$) with C18:0 addition than the unsaturated fatty acid additions (.18 vs .16 ± .01 mL/h). Disappearance of DM was not affected by fatty acid addition which averaged 30.0% ± 1.1 at 24 h. Fatty acid addition decreased *Isotrichia spp.* numbers from .7 x 10^4 to .5 x 10^4 ± .05/mL without affecting *Entodinium spp.* or *Polyplastron spp.* numbers. These results were in contrast to Criswell et al. (1996) who noted decreased protozoal numbers and fiber digestion, in vivo, with fat addition. However, the current results were similar to Wedam's (1999) in vitro study.

Epifluorescence micrographs showed decreasing blue-green epifluorescence (methanogenic endosymbionts) with unsaturated fatty acid addition and much smaller protozoal volume when C18:3 was added. This suggests decreased methanogenesis with the more unsaturated fatty acid additions.

Rate of gas accumulation, DM disappearance and *Isotrichia spp.* and *Polyplastron spp.* numbers were not affected by fatty acid addition to the alfalfa substrate. However, *Entodinium spp.* numbers were quadratically decreased ($P < .05$) by degree of unsaturation of fatty acid added. Minimum *Entodinium spp.* were noted when C18:1 was added (4.4 ± .3 x 10^4 mL) and maximum numbers were noted when C18:0 was added (6.6 ± .3 x 10^4 mL). These results are in contrast to in vivo results of Smith et al. (1993), Wu

et al. (1993), and Wedam (1999) who suggested fat was inert in alfalfa diets. Micrographs showed no change in epifluorescence (methanogenic endosymbionts) with unsaturated fatty acid addition. However, it appears that C18:0 addition resulted in increased protozoal mass. This suggests maintained or increased methanogenesis with fatty acid additions.

We concluded that with barley as the substrate, fatty acid addition decreased methanogenic endosymbionts without decreased *Entodinium spp.* numbers. However, with alfalfa as the substrate, fatty acid addition did not affect methanogenic endosymbionts but apparently increased *Entodinium spp.* volume and numbers when C18:0 was added. Therefore, the association between endosymbionts and *Entodinium spp.* was not obligate for *Entodinium spp.* survival and growth but due to decreased protozoal numbers, the association between endosymbionts and *Entodinium spp.* may have been obligate for *Entodinium spp.* survival and growth with alfalfa as the substrate.

In summary, composition and feeding value depends on which potato by-product is available. However, most are suitable energy sources for finishing cattle fed barley diets. Fats and oils have more variable energy value due to interaction with diet ingredients and microbial fermentation.

Table 1. Composition of potato by-products

Item	Peels[a]	Hopper box[b]	Potato slurry[c]	Potato slurry[d]	Peels[e]	Fries[e]
			% of DM			
CP	9.8	11.6	4.7	12.2	17.2	5.6
Starch	56.3	55.9	NR[f]	NR	34.8	NR
NDF	12.8	21.0	NR[c]	NR[d]	20.8	4.4
ADF	9.2	17.4	NR	NR	1.2	NR
Ash	7.6	4.7	15.5	13.0	1.1	1.9
EE	NR	NR[b]	6.3	.25	NR	22.0

[a]Duncan et al. (1991).
[b]Nelson et al. (2000). Total fatty acid was 1.7%.
[c]Heinemann and Dwyer (1972b). Crude fiber was 5.4%.
[d]Heinemann et al. (1978). Crude fiber was 3.3%.
[e]Rooke et al. (1996). 3.5:1 unsaturated:saturated fatty acid in fries.
[f]NR = not reported.

Table 2. Effect of level of potato slurry on finishing steer performance[a]

	% Potato slurry				
Item	0	15.4	27.8	42.5	51.9
DM intake, kg/d	9.0	9.3	8.8	9.1	8.5
Average daily gain, kg/d[b]	1.3	1.3	1.3	1.3	1.2
Feed-to-gain	6.7	7.2	6.6	6.9	7.1
Dressing percent[b]	62.8	63.5	62.9	61.8	60.0

[a]Heinemann and Dyer (1972).
[b]Lower ($P < .05$) for 51.9% potato slurry.

Table 3. Linear barley by potato process residue interaction for in vitro insoluble DM disappearance kinetics[a]

	Grain treatment			
Potato residue, %	100% Corn	67% Corn 33% Barley	33% Corn 67% Barley	100% Barley
	Discrete lag phase, h[b] ($P < 0.05$)			
0	3.6	2.6	3.2	1.5
14	5.8	5.1	3.4	1.1
	Rate of DM disappearance, %h[c] ($P < 0.10$)			
0	7.4	6.6	9.1	8.7
14	8.2	9.5	9.8	8.3
	Extent of disappearance, %[d] ($P < 0.01$)			
0	81.2	83.4	81.9	81.4
14	84.2	83.2	80.4	77.4

[a]Duncan et al. (1991).
[b]SE = 0.53.
[c]SE = 0.60.
[d]SE = 1.11.

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