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The effects of pelleting hay upon feed intake, digestibility, growth rate and energy retention of lambs

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ABSTRACT
This paper reports three trials that evaluated the effects of pelleting hay upon feed intake, digestibility, growth rate and energy utilisation of 7-9 month old, castrated male lambs. In the first trial, hay and pellets were compared on three feeding levels. The second study had a similar arrangement of treatments and an additional comparison of two types of hay. The third trial had three treatments with different combinations of whole hay and pellets ad libitum. In the first two trials the lambs were individually fed, and in vivo digestibility was measured. In the third trial, feed intake was measured on a group basis. Pelleting increased ad libitum feed intake by 40-75%. Digestibility was negatively affected by pelleting, but the overall effect of pelleting on growth rate was positive. Measurements of energy retention indicate that the negative effect of pelleting on digestibility was compensated by better utilisation of digestible energy into net energy.

Keywords: feed processing, forage, feed intake, growth rate, digestibility, energy retention, lambs.

YFIRLIT
Áhrif kögglunar heys á át, meltanleika, vaxtarhraða og orkunýtingu lamba
Þrjár tilraunir sem hér er sagt frá lögðu mat á áhrif þess að köggla hey á daglegt át, meltanleika, vaxtarhraða og orkunýtingu hjá 7-9 mánaða gömlum sauðum. Í fyrstu tilrauninni var hey og kögglar borið saman við þrjú fóðrunarstig. Önnur tilraunin hafði svipað skipulag tilraunameðferða, en að auki var þar samanburður á tveimur heygerðum. Í þriðju tilrauninni voru þrjár meðferðir með mismunandi samsetningum heys og köggla eftir átlyst. Í fyrri tveimur tilraununum voru lömbin einstaklingsfóðruð og in vivo meltanleiki mældur. Í þriðju tilrauninni var fóðurát metið á hópagrunni. Kögglun jók daglegt át um 40-75% þegar fóðrað var eftir átlyst. Kögglunin hafði neikvæð áhrif á meltanleika en jákvæð áhrif á vöxt lambanna. Mælingar á orkusöfnun lambanna gefa til kynna að hin neikvæðu áhrif kögglunarinnar á meltanleika hafi verið bætt upp með betri nýtingu meltanlegrar orku yfir í nettóorku.

INTRODUCTION
It has long been known that, because of reduced particle size, ground, pelleted forages pass through the ruminant forestomachs faster than long or chopped material. This results in increased maximum daily feed intake but lower digestibility of the forages, as the fibrous feed components have less time to ferment in the rumen (Blaxter et al. 1956, Greenhalgh & Reid 1973). The overall effect of grinding/pelleting on the production value of forage feeds is dependent on several factors, like the digestibility of the intact forage, the animal species, its production level and type of production (Greenhalgh & Reid 1973).

In the late 20th century, a great effort was put into grass pelleting factories in Iceland. It peaked at the level of 13.000 tonnes produced in the early 1980s with one private- run and five state-run factories located in different parts of the country. The artificial drying of the grass in these factories was driven by fossil fuels (Stefánsson 1980). Volatile prices of fuels and overproduction of grass pellets after the maximum production capacity had been achieved resulted in operational difficulties (Franksson 1980), so these factories were closed one after another, the last one shortly after the turn of the century. Also, in the last three decades of the 20th century, up to five portable hay pellet factories were run in Iceland, producing up to 5.000 tonnes per year, one of which has been active from time to time.

Although the overall operating basis of pelleting forage has probably been somewhat overrated by the pioneers, it is evident that there was a considerable market for these products in Iceland. Several experiments were made with grass and hay pellets for cattle (Ólafsson 1972 & 1978) and sheep (Lárusson et al. 2006, Lárusson & Sveinbjörnsson 2007, Lárusson & Sveinbjörnsson 2016). Considerable effort was also made to adopt knowledge from international studies regarding the effects of pelleting on forage feed efficiency (Mundell & Eiríksson 1980, Sigurðsson & Lárusson 1980).

The possibilities of using more sustainable and domestic energy resources, like electricity and geothermal energy, for artificial drying of grass for pelleting, were explored to some extent around 1980 with promising results (Stefánsson 1980). Present day circumstances regarding energy prices and volatilities in international feed markets suggest in many ways that these plans should be revisited. Also, the infrastructure regarding electrical and geothermal energy has moved very much forward in Iceland in the last decades, and there is a public interest in increasing the use of these resources in feed and food production.

In this paper, three trials dealing with the effects of pelleting hay for growing lambs will be reported in more detail than previously. Preliminary reports in Icelandic (Lárusson et al. 2006, Lárusson & Sveinbjörnsson 2007) and a conference paper in English (Lárusson & Sveinbjörnsson 2016) did not take advantage of all the data collected in the trials. It is important to do so now, not only because of the renewed interest in the effects of pelleting forage, but also because there is a general lack of results to prove or disprove the adequacy of the energy evaluation system that is publicly in use for sheep in Iceland. The purpose of this paper is therefore to fully exploit the results of these three trials and relate them to relevant information from the literature, which will provide a basis for new and more detailed studies. Aspects examined here in more detail than in former reports are the effects of pelleting on energy retention and how that compares with growth predicted by the energy evaluation system currently in use for sheep in Iceland.

MATERIALS AND METHODS

Trials

The first two trials (HT-85 and HT-87) were conducted on the state-run research farm Skriðuklaustur in eastern Iceland in the years 1985 and 1987. The third trial (VB-05) was conducted in 2005 on a private farm Vörðubrún, also in Eastern Iceland. In trials HT-85 and HT-87 in vivo digestibility and energy content of total empty body were determined for all lambs in the study. Due to the intense data collection, the number of lambs in each treatment was limited to four, but as all measurements, including feed intake, were on an individual lamb basis, each lamb was treated as a replica in all statistical analyses. The third trial (VB-05) was a follow-up production study with a total of 16 lambs per treatment, divided into two 8-lamb groups for measurement of feed intake.

Animals

Castrated male lambs of the Icelandic sheep breed were used in the trials. In all three trials, relatively-small ram lambs (27-30 kg) were selected at weaning at 4-5 months of age in September/October and fed indoors on hay until the trials started in January/February. The lambs were castrated in November and shorn in December. Although the lambs in the three trials had similar weight when they were selected in the autumn, there were differences between trials in the average live weights at the initiation of the trials: 31.2, 34.0 and 39.2 kg in trials HT- 85, HT-87 and VB-05, respectively. Feed intake was tested in January. All lambs were weighed and assigned to treatments so that the average initial live weight of each treatment group within a trial was as equal as possible. At the initiation of the trials, control groups were slaughtered. The first week of the trials was an adaptation period; thereafter the formal trial started, which lasted around 10 weeks.

Experimental treatments

In all three trials, hay was compared with pellets that were made from the same hay by milling in a hammer mill to pass a 6-mm screen in a pellet press. In the first trial (HT-85), there were three feeding levels (maintenance, 1.5 x maintenance and ad lib) with only hay vs 200 g/d hay + pellets from the same hay. The maintenance level was defined as the intake level needed to fulfill maintenance requirements, with feed energy values calculated from in-vitro digestibilities irrespective of the possible effects of pelleting on energy utilization. The second study (HT-87) had the same arrangement of treatments but an additional comparison of two types of hay from the same sward cut at two different dates. Also, the 1.5 x maintenance was the highest feeding level for hay, whereas for pellets there was an additional higher feeding level, i.e. ad lib. This was based on experience from the first study, where lambs were close to ad lib feeding at the

Table 1. Experimental treatments and feed plan

Experiment/ Treatments	No. lambs	Feed[a]	Feeding level
HT-85			
A	4		Slaughtered at initiation of experiment
B	4	Hay	Maintenance
C	4	Pellets+200 g hay	Maintenance
D	4	Hay	1.5 x maintenance
E	4	Pellets+200 g hay	1.5 x maintenance
F	3	Hay	Ad lib.
G	4	Pellets+200 g hay	Pellets ad lib
HT-87			
A	4		Slaughtered at initiation of experiment
BI	4	Hay c1	Maintenance
BII	4	Hay c2	Maintenance
CI	4	Pellets and 200 g hay, both from cut 1	Maintenance
CII	4	Pellets and 200 g hay, both from cut 1	Maintenance
DI	4	Hay c1	1.5 x maintenance
DII	4	Hay c2	1.5 x maintenance
EI	4	Pellets and 200 g hay, both from cut 1	1.5 x maintenance
EII	4	Pellets and 200 g hay, both from cut 2	1.5 x maintenance
FI	4	Pellets and 200 g hay, both from cut 1	Pellets ad lib
FII	4	Pellets and 200 g hay, both from cut 2	Pellets ad lib
VB-05			
V	2x8		Slaughtered at initiation of experiment
A	2x8	Hay	Hay ad lib
B	2x8	Pellets + 300 g hay	Pellets ad lib
C	2x8	Hay + 300 g pellets	Hay ad lib

[a]cut1=cutting date 1 (early); cut2= cutting date 2 (late)

1.5 x maintenance feeding level for hay but not for pellets. In the third trial (VB-05), there was only one feeding level (ad lib) and only one type of hay, which was either fed as a) whole hay, b) 300 g whole hay + pellets ad lib or c) 300 g pellets + whole hay ad lib. The experimental treatments are listed in more detail in Table 1.

Animal measurements

In the first two trials, HT-85 and HT-87, the lambs were individually fed and in vivo dry matter digestibility was measured. Feed intake was measured on a DM basis as the difference between feed offered and feed refusals, averaging two daily measures per week for each lamb throughout each experiment. The in vivo dry matter digestibility measurement was based on a collection of faeces for six consecutive days, with daily registration of feed intake and feed refusals starting one day earlier and ceasing one day sooner than the feaces collection. Dry matter digestibility was calculated using the general formula: digestibility = (DM consumed – DM in feaces)/DM consumed (McDonald et al. 2011). Live weight (LW) was measured (0.1 kg of accuracy) two weeks before the experiment started, at the initiation of the experiment, at 1-2 week intervals through the experiment and finally at the day before slaughter. Daily gain was assessed as the difference between the LW at the day before slaughter and the LW at the initiation of the experiment, divided by the number of days in between. In the first (HT-85) and second (HT-87) trials, the comparative slaughter technique (McDonald et al. 2011) was used to measure the energy retention resulting from different experimental treatments. The total empty body energy in the initial slaughter groups A in trials HT-85 and HT-87 was subtracted from the total empty body energy in the respective treatment groups (Table 1) to measure the energy retained by different treatments. In the third trial (VB-05) lambs were group fed. Feed intake was measured on a group basis and live weight was measured regularly. Carcass weight and weight of omental fat were registered.

Analysis of empty body in trials HT-85 and HT-87

At slaughter, blood was gathered and weighed. The fleece was cut off and weighed separately. The digestive organs were emptied and their contents (digesta) weighed separately, as was the carcass, fleece-free skin, head, feet, liver, other internal organs, internal fat, and other tissues. The energy content of the empty body (everything except the digesta) was assessed as gross energy by bomb calorimeter and/or by estimation from chemical analysis, assuming 39.3 and 23.6 MJ per kg fat and protein, respectively (McDonald et al. 2011). Energy estimations were made for the carcass and wool separately, but all other parts were combined, minced, mixed, and analyzed. These “other parts” include fleece-free skin, head, feet, empty gut, liver and other internal organs. Digesta contents were not analyzed, as they are not considered to be retained energy. The carcasses were frozen and split in two halves longitudinally. In trial HT-85, one half of one carcass from each of the seven treatment groups (including the control group A) was minced and mixed for chemical analysis. From the other half of these carcasses, slices were made by sawing the carcasses transversely at ca 2-cm intervals. The slices and the sawdust were collected separately, minced and mixed. Energy values for these seven lambs obtained by gross energy analysis (bomb calorimeter) of the three sample types, i.e., carcass, slices and sawdust, were compared. The average values for each method of respectively 27.92, 28.08 and 28.07 MJ per kg were not significantly different ($P>0.99$). Gross energy values were also calculated from chemical analysis of the same samples. These results were 28.25, 28.48 and 28.49 MJ per kg for the carcass, slices and sawdust, respectively, the differences among sample types also not significant. When run as a two-way analysis of variance with the seven lambs as replicates, both the main effects of sample type (carcass, slices, sawdust) and energy determination method (direct or estimated from chemical analysis), as well as their interactions, were non-significant. Based on this comparison, one half of all the carcasses in the study were sawed in slices as explained above, and the

Table 2. In vitro dry matter digestibility, energy value FE_m (Sveinbjörnsson & Ólafsson 1999), ash and crude protein content of the hay used in the experiments.

Experiment[a]	Dry matter digestibility %	Energy, FEm kg DM^{-1}	Ash g kg DM^{-1}	Crude protein g/kg DM
HT-85	63.5	0.70	88.4	130
HT-87 – cut 1	68.5	0.77	78.2	170
HT-87 – cut 2	58.5	0.63	80.5	105
VB-05	67.0	0.75	95.2	137

[a]cut1=cutting date 1 (early); cut2= cutting date 2 (late)

sawdust was used for further analysis. Reported gross energy values for carcasses in trials HT-85 and HT-87 were based on calculations of gross energy from chemical analysis of the sawdust. For other body parts, reported values were from bomb calorimetry measurements.

Chemical analysis

The feed analyses presented in Table 2 were done on the whole hay that was used as such in the experiments and as a raw material for the hay pellets. In vitro dry matter digestibility was analysed by the method of Tilley & Terry (1963), and crude protein was measured using the Kjeldahl method.

For analysis of the lamb carcasses, protein was also measured by the Kjeldahl method, and crude fat was analysed by the Soxhlet method (AOAC 1990). Gross energy was measured in a bomb calorimeter (Harris 1970).

Statistical analysis

Statistical analyses were performed in SAS (2015). PROC GLM was used for simple ANOVA analysis and calculating least square means as presented in Tables 3, 4 and 6. A paired *t*-test assuming unequal variances was used for comparing energy utilisation efficiency of hay vs pellet treatments, as reported in Table 5. PROC REG was used for the linear regressions reported in Table 7. Graphs (Figures 1, 2a and 2b) were plotted in Microsoft® Office Excel.

Calculations of retained energy and energy utilisation efficiency

Retained energy was calculated as the difference between the average energy content of the empty body, including empty gut, of lambs at slaughter and the estimated average energy content of the empty body of lambs at the start of the experiment. The latter was estimated from the initial LW of the lambs by applying the following regression formula: Y=8.51 x LW – 2.66; where Y is MJ energy in empty body. This formula (r^2=0.55) was fitted from data of the 8 lambs belonging to the control groups A in trials HT-85 and HT-87.

Calculations of energy utilization efficiency, as reported in Table 5, Figure 2a and Figure 2b were made with reference to the energy evaluation system in use for sheep in Iceland. Since it has only been reported in Icelandic (Sveinbjörnsson & Ólafsson 1999), it is necessary to point out the basis for how that system has been applied for Icelandic sheep, and in this context especially for growing lambs. The calculation of feed energy values (milk feed units, FE_m) was based on the Dutch system by Van Es (1978). The energy requirements for maintenance were adapted to Icelandic sheep by reference to the Dutch (Van Es 1978) and French (Bocquer & Thériez 1989) systems but with a special energy allowance made for the effect of shearing in variable climates, based on the Australian system (CSIRO 1990). That system was also used to derive the requirements for lamb growth.

RESULTS

In trial HT-85 (Table 3), the in vivo digestibility of the hay fed at the intended maintenance level (B) was equal to the in vitro digestibility estimate. Actual maintenance level was not reached, however, as can be seen from negative values for the daily growth rate and retained energy for treatment B. The same daily intake with the pellet-treatment C, as with hay-treatment B, resulted in four percentage points lower in vivo digestibility but better performance, close to maintenance level. With the intended 1.5 x maintenance level, the intake in the hay-treatment D was lower than expected and significantly lower than in the pellet-treatment E. Also, for the intended ad lib hay treatment F, the intake was not significantly higher than in treatment D, meaning that ad lib intake was already reached in treatment D. The ad lib intake in the pellet treatment G was more than 50% higher than in the hay treatments (D and F). At all feeding levels, pelleting resulted in a considerable decrease in in vivo digestibility but improved animal performance, as can be seen from several variables reported in Table 3, best summarized by looking at the results for retained energy.

In trial HT-87 (Table 4) the first cut of the forage was better and the second cut poorer than for the hay used in HT-85, judging from in vitro digestibility values reported in Table 2. The results in Table 4 showed, however, in general a better performance of the lambs regarding growth and energy retention, also for the second cut hay, than in trial HT-85. In the hay treatments in vivo digestibility was maintained at 71 and 65 (considerably higher than in vitro estimates) for cut 1 and cut 2 respectively, when feeding level was increased (B vs D treatments). Based on the experience from trial HT-85, there were only two feeding levels for the hay but three for the pellets in HT-87. Like in the former trial, pelleting resulted in considerably lower in vivo digestibility. Here, however, differences in lamb performance were small and not statistically significant between hay and pellet diets at comparable feeding levels and forage cuts. By ad lib feeding of pellets (F treatments), daily intake was close to what was found in HT-85, and the lamb performance (Table 4) better than seen in other treatments in these two trials.

Pelleting in studies HT-85 and HT-87 resulted in decreased in vivo digestibility and

Table 3. The effect of treatments in experiment HT 85 on dry matter intake (DMI), in vivo digestibility, live weight gain (LWG), carcass weight, empty body weight (EBW), energy content per kg EBW, total energy in empty body, and retained energy (RE) in empty body found by comparison with control group (A), as explained in text.

Treatm.$^{*)}$	DMI kg d^{-1}	DM-Digestibility in vivo %	LWG g d^{-1}	Carcass kg	Abdom. fat, kg	EBW, kg	MJ kg EBW^{-1}	MJ in empty body	RE, MJ in empty body
A				12.24^{ab}	0.98^{a}	22.16^{ab}	11.29^{ab}	249.0^{ab}	
B	0.725^{a}	63.54^{c}	-17.9^{a}	10.85^{a}	0.43^{a}	19.65^{a}	9.14^{a}	181.5^{a}	-71.1^{a}
C	0.732^{a}	59.29^{bc}	8.9^{ab}	12.71^{ab}	0.72^{a}	22.87^{ab}	10.58^{ab}	245.0^{ab}	-0.2^{ab}
D	0.935^{b}	65.90^{c}	21.4^{ab}	12.99^{ab}	1.02^{a}	23.78^{ab}	10.96^{ab}	260.4^{ab}	-2.9^{ab}
E	1.023^{c}	57.22^{b}	33.9^{b}	14.90^{b}	1.16^{a}	26.48^{b}	11.56^{ab}	307.4^{bc}	39.9^{b}
F	0.963^{bc}	63.33^{c}	0.0^{ab}	13.37^{ab}	0.81^{a}	24.40^{ab}	10.30^{ab}	253.2^{ab}	-30.6^{ab}
G	1.506^{d}	51.70^{a}	89.3^{c}	16.58^{b}	2.01^{b}	30.11^{b}	12.35^{b}	371.5^{c}	99.7^{bc}
SEM	0.014	1.03	11.3	0.65	0.18	1.01	0.62	21.7	18.1

$^{a, b, c}$: Values with different superscript within a column are statistically different, $p<0.05$.

SEM: standard error of the means

$^{*)}$Treatments: A: control – slaughtered at the initiation of the experiment; B: Hay- maintenance; C: Pellets + 200 g hay- maintenance; D: Hay-1.5 x maintenance; E: Pellets + 200 g hay – 1.5 x maintenance; F: Hay ad lib.; G: 200 g hay + pellets ad lib.

Table 4. The effect of treatments in experiment HT-87 on dry matter intake (DMI), in vivo digestibility, live weight gain (LWG), carcass weight, empty body weight (EBW), energy content per kg EBW, total energy in empty body, and retained energy (RE) in empty body found by comparison with control group (A), as explained in text.

Treatm.$^{*)}$	DMI kg d^{-1}	Digest-ibility in vivo %	LWG g d^{-1}	Carcass kg	Abdom. fat, kg	EBW, kg	MJ per kg EBW	MJ in empty body	RE, MJ in empty body
A				13.35^{ab}	1.66^{ab}	24.88^{ab}	11.64^{a}	291.4^{ab}	
BI	0.656^{a}	71.88^{c}	31.3^{ab}	14.54^{ab}	1.04^{ab}	25.92^{ab}	11.68^{a}	305.8^{ab}	32.9^{ab}
BII	0.665^{a}	65.89^{bc}	1.8^{a}	13.24^{a}	0.69^{a}	23.65^{a}	12.01^{a}	284.3^{ab}	4.0^{a}
CI	0.674^{a}	67.92$_{bc}$	33.1^{ab}	14.67^{ab}	0.84^{a}	25.71^{ab}	12.16^{a}	313.5^{ab}	35.3^{ab}
CII	0.695^{a}	59.62^{ab}	-5.5^{a}	13.92^{ab}	0.63^{a}	24.62^{ab}	11.44^{a}	282.8^{a}	6.8^{a}
DI	0.928^{b}	71.12^{c}	73.5^{b}	16.56^{ab}	1.45^{ab}	29.82^{ab}	13.15^{a}	391.6^{ab}	94.3^{ab}
DII	0.802^{b}	65.65^{bc}	22.1^{ab}	14.17^{ab}	0.80^{a}	25.38^{ab}	11.57^{a}	295.6^{ab}	2.5^{a}
EI	0.968^{b}	66.21^{bc}	62.5^{b}	16.82^{ab}	1.49^{ab}	30.16^{ab}	13.08^{a}	394.5^{ab}	105.7^{b}
EII	0.855^{b}	60.41^{ab}	20.2^{ab}	14.43^{ab}	1.28^{ab}	25.86^{ab}	13.10^{a}	340.0^{ab}	56.5^{ab}
FI	1.473^{c}	62.07^{b}	139.7^{c}	19.07^{b}	2.45^{b}	35.34^{b}	13.82^{a}	492.5^{b}	204.7^{c}
FII	1.435^{c}	55.29^{a}	101.1^{bc}	17.26^{ab}	1.59^{ab}	31.81^{b}	13.33^{a}	426.0^{ab}	125.5^{bc}
SEM	0.043	1.23	10.7	0.88	0.31	1.52	0.51	30.7	20.1

$^{a, b, c}$: Values with different superscript within a column are statistically different, $p<0.05$.
SEM: standard error of the means
Treatm.$^{*)}$: A:control - slaughtered at the initiation of the experiment; BI:Hay cut 1 – maintenance; BII: Hay cut 2 – maintenance; CI: Pellets and 200 g hay, both from cut 1 – maintenance; CII: Pellets and 200 g hay, both from cut 2 – maintenance; DI:Hay cut 1 – 1.5 x maintenance; DII: Hay cut 2 – 1.5 x maintenance; EI: Pellets and 200 g hay, both from cut 1 – 1.5 x maintenance; EII: Pellets and 200 g hay, both from cut 2 – 1.5 x maintenance; FI: 200 g hay and pellets ad lib., both from cut 1; FII: 200 g hay and pellets ad lib., both from cut 2;

Table 5. Trials HT-85 and HT-87: energy utilisation efficiency = (retained energy+calculated maintenance requirements)/calculated energy value of hay vs pelleted diets, based on in vitro vs in vivo digestibilities.

	Based on in vitro dig.		Based on in vivo dig.	
	Hay	Pellets	Hay	Pellets
HT-85maintenance (B vs C)	0.54	0.82	0.54	0.90
HT-85 1.5 x maintenance (D vs E)	0.68	0.75	0.64	0.86
HT-85 ad lib (F vs G)	0.60	0.65	0.60	0.85
HT-87 maintenance cut 1 (BI vs CI)	1.05	1.03	0.99	1.05
HT-87 maintenance cut 2 (BII vs CII)	1.12	1.06	0.96	1.04
HT-87 1.5 x maintenance cut 1 (DI vs EI)	0.99	0.97	0.94	1.01
HT-87 1.5 x maintenance cut 2 (DII vs EII)	0.98	1.10	0.84	1.06
Average	**0.85**	**0.91**	**0.79**	**0.97**
Significance (t-test)	P=0.20		P<0.01	
HT-87 pellets ad lib cut 1 (FI)	0.87		0.99	
HT-87 pellets ad lib cut 2 (FII)	0.89		0.96	

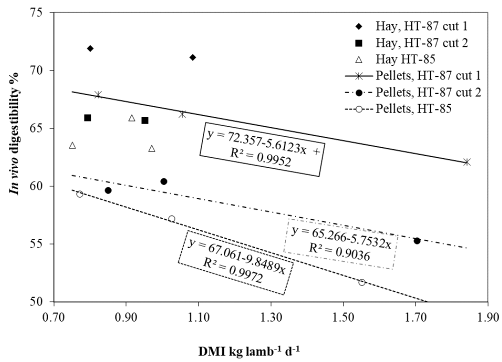

Figure 1. Trials HT-85 and HT-87: The effect of daily feed dry matter intake (DMI) upon in vivo digestibility of hay and hay pellets with different in vitro digestibilities as presented in Table 2. Note that DMI values are means for the period when digestibility was measured and therefore not exactly the same as overall means reported in Table 3 and Table 4.

increased maximum intake (Fig. 1). The intake increase itself (within the same raw material) clearly decreased in vivo digestibility of the pelleted diets, but an increased intake (feeding level) in hay diets did not have as clear an effect on in vivo digestibility.

Table 5 reports the efficiency of energy utilization for hay vs. pelleted diets in trials HT-85 and HT-87 at two different biological levels, i.e., either from ingested or digested energy as a starting point towards net energy as a final point. The ratios in Table 5 showed to what extent calculated energy values of the feed according to the FE_m-system (Van Es 1978) were covered by the energy response of the animals, i.e., the retained energy plus calculated maintenance requirements. First, these ratios are reported as they appear if the energy values of the feed are based on the in vitro digestibility estimates of the intact hay. That comparison reports possible differences in total energetic feed efficiency from ingested material to net energy. The paired *t*-test, based on comparisons where pairs are treatments with hay vs pellets at comparable feeding levels, showed a tendency but not a significant difference (P=0.20) in the favour of pelleted diets. Second, in Table 5 the reported ratios for feed efficiency were calculated in the same way as the former values, except that feed energy values were based on the in vivo digestibility found in the trials. The comparison of hay vs pellet treatments

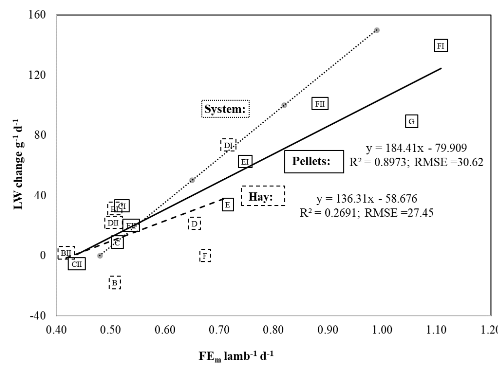

Figure 2a. Trials HT-85 and HT-87: The effect of available net energy (FE_m lamb^{-1}d^{-1}) based on in vitro digestibilities (see text) upon lamb LW change, for hay vs pelleted diets, compared to growth predicted by the current Icelandic energy evaluation system (Sveinbjörnsson & Ólafsson 1999). RMSE = root – mean- squared error, i.e. the prediction error of the regression equations.

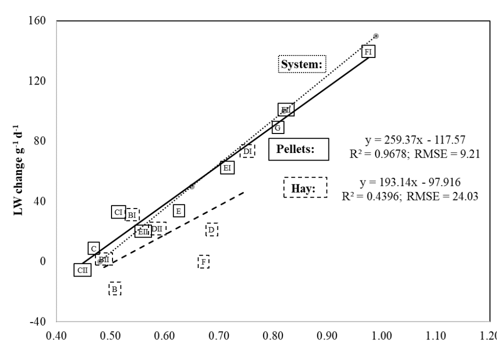

Figure 2b. Trials HT-85 and HT-87: The effect of available net energy (FE_m lamb^{-1}d^{-1}) based on in vivo digestibilities (see text) upon lamb LW change, for hay vs pelleted diets, compared to growth predicted by the current Icelandic energy evaluation system (Sveinbjörnsson & Ólafsson 1999). RMSE = root – mean- squared error, i.e. the prediction error of the regression equations.

Table 6. Trial VB-05: Dry matter intake (DMI), live weight on the day before slaughter, weight of carcass and abdominal fat and the daily gain of live weight (LWG) and carcass.

Treatm. *)	DMI kg d^{-1}	LW, kg	Carcass, kg	Abdom. fat, kg	LWG g d^{-1}	Carcass gain g d^{-1}
V		37.38[a]	15.04[a]	1.20[a]		
A	1.243[a]	49.88[b]	18.73[b]	1.38[a]	148.5[a]	51.3[a]
B	1.667[b]	56.06[c]	21.43[c]	2.79[b]	218.8[b]	88.8[b]
C	1.315[a]	51.06[b]	19.65[b]	1.83[a]	153.6[a]	64.1[a]
SEM	0.036	1.11	0.40	0.16	7.4	2.9

Treatm.*): V:control - slaughtered at the initiation of the experiment; A: Hay ad lib.; B: 300 g hay + pellets ad lib.; C: 300 g pellets + hay ad lib.

accounted for what happens after digestion and showed that digestible energy was converted to net energy with considerably better efficiency for pelleted than for hay diets. Although the ad lib pellet treatment in trial HT-87 did not have any corresponding hay treatment, the efficiency ratios are also reported for that treatment at the bottom of the table.

Figures 2a and 2b further report the differences between hay and pelleted diets in efficiency of energy utilization and compare them with the growth response predicted by the public energy evaluation system (Sveinbjörnsson & Ólafsson 1999). Figure 2a reports the conversion of ingested energy to net energy, as the ingested energy would be evaluated if nothing was known about the effects of pelleting and feeding level upon actual digestion, i.e., the feeding values on the x-axis are based on in vitro digestibility of intact hay. The energy evaluation system overestimates the growth response compared to the actual responses, but the differences in this regard are smaller and more regular with the pelleted diets than the hay diets.

Figure 2b reports the conversion of digested energy to net energy, as the feeding values on the x-axis are based on the in vivo digestibility. The digested energy was more efficiently converted to maintenance and growth for the pelleted diets, which also showed a much more consistent relationship between energy intake and growth than the hay diets. The digested energy from the pelleted diets was utilised for maintenance and growth, almost as the energy evaluation system predicts.

The follow-up production trial VB-05 is reported in Table 6. Lambs were somewhat more mature initially than in the other trials, and the final live and carcass weights were considerably greater. The ad lib intake of intact hay (Treatment A) was on average 2.79% of LW, which can be compared to the other "ad lib" hay treatments: 2,85% and 2,86% in D and F treatments in trial

Table 7. Equations predicting total energy (MJ) in empty body from 1 to 3 explanatory variables, based on data from trials HT-85 and HT-87.

	Intercept	Regression coefficients on: Carcass kg (SE)	MJ per kg carcass	Abdom. fat, kg	R^2 RMSE
Equation 1	-128.8 (33.2)	29.61 (2.45)			0.85 26.6
Equation 2	-242.4 (15.9)	19.21 (1.28)	22.23 (1.85)		0.98 10.2
Equation 3	-18.1 (23.3)	16.52 (2.18)		62.88 (8.20)	0.96 14.6
Equation 4	-157.1 (17.7)	16.06 (0.98)	15.77 (1.62)	29.67 (5.02)	0.99 6.6

HT-85; 2.44 and 2.23 in DI and DII treatments in trial HT-87. Similarly, the ad lib intake of pellets is 3.46% of LW in treatment B in trial VB05, which can be compared to the other "ad lib" pellet treatments: 4.25 % in G treatment in HT-85; 3.72 and 3.64% in FI and FII treatments in HT-87.

Regression analyses reported in Table 7, based on data from trials HT-85 and HT-87, showed that carcass weight alone explained 85% of the variation in total empty body energy, but 98% and 96% was explained if energy content per kg carcass or weight of abdominal fat were added as a second explanatory variable. If all three explanatory variables were included, 99% of the variation in total empty body energy was explained, and the prediction error was reduced compared to the simpler models.

DISCUSSION

Permanent leys of grasses and legumes can in many regions capture more energy in biomass than annual crops like grain. Despite that, large quantities of grain concentrates are commonly fed to ruminants in these regions (Huhtanen & Hristov 2009). A main reason for that is the difficulty of supplying high-producing animals with energy because of the limited intake capacity of forage. The effects of grinding and pelleting forages on their intake and utilisation by ruminants were extensively studied after the middle of the twentieth century, when the international trade of grain-based concentrates was not as extensive as it later became. Blaxter et al. (1956) conducted digestibility trials on wether sheep and found that ground, pelleted grass meal had higher passage rate and lower digestibility than the same hay unground, fed in the same daily amount. Furthermore, they found that increasing the feeding level increased the feed passage rate and decreased digestibility, especially for pellets made from finely ground material. In a parallel study on the same animals, Blaxter & Graham (1956) found no significant differences between grinding and pelleting on energy retention or actual net energy values of the forage. Increased faecal energy losses were compensated by decreased losses of energy as heat and methane.

Rodrigue & Allen (1960) conducted digestibility trials with dairy cows, where they found that passage rate increased and digestibility decreased when hay was ground to an increasing degree of fineness. A marked decrease in milk fat percentage due to grinding was also associated with a large depression in the digestibility of cell wall constituents. Campling et al. (1963) found that grinding and pelleting hay for dry cows decreased digestibility by almost one third at ad lib feeding, but the effects on intake were not significant. When fed in smaller rations, the negative effect of grinding on digestibility was smaller but still substantial. These results were a good example of no benefit from grinding forage; such costs are wasted on low producing animals. There were also indications that the positive effects of grinding experienced with sheep were not necessarily valid for larger ruminants. Campling & Freer (1966) further studied the effects of grinding and pelleting two types of forage for dry cows - highly digestible grass hay and oat straw of low digestibility. The grass hay did not benefit from pelleting, as digestibility decreased but feed intake was unaffected; whereas for the oat straw, the fall in digestibility was less severe and intake was increased by 26%. These results agreed with conclusions from studies reviewed by Minson (1963) that less benefit is normally obtained from grinding and pelleting a high- than a low-quality roughage.

Greenhalgh & Reid (1973) found that pelleting forage increased intake (average of three diets) by 45% in sheep, but only 11% in cattle. The digestibility was reduced by 13 percentage points in sheep but 19 points in cattle. The increase in intake was greater for low- than for high-quality grass and greater for younger than older animals of both species. It was hypothesised that variable threshold regarding particle size of food to pass out of the rumen could explain interactions between form of forage on one hand and species and age of animal and diet composition on the other hand.

The above-mentioned studies were

pioneering in understanding the relationships between particle size, rate of intake, rate of passage and digestibility, accounted for in modern ruminant feed evaluation systems. Basically, effective digestibility (or degradability) of feed or feed component in the rumen and/or other digestive organs is dependent on its potential digestibility, rate of degradation and rate of passage. Effective digestibility is positively related to the first two of these variables, but negatively to passage rate (Waldo et al. 1972). If passage rate is increased and the other two variables remain stable after feed processing, effective digestibility will decrease.

A fundamental issue to help understand the effect of forage particle size on intake, digestibility, and overall energy utilization and how that is somewhat different between large ruminants like dairy cattle and small ruminants like sheep is to consider the threshold for the feed to pass out of the ruminant forestomach through the reticulo-omasal orifice. The control of this passage is complicated (Okine et al. 1998). The size of the reticulo-omasal orifice, positively related to size of the animal, is only one of the factors to consider. It is clear, however, that physical processing of rough feed material to decrease its particle size increases passage rate more for small than large ruminants, with positive effects on feed intake but negative effects on digestibility. The main reason for why this benefits small ruminants more than the larger ones is the important biological differences related to body size. The volume of the reticulorumen increases in direct proportion to body weight, whereas maintenance energy requirements increase in relation to metabolic body weight, i.e. $BW^{0.75}$. This means that the maintenance requirements of a 600-kg cow are only seven times greater than that of 60-kg sheep, whereas the capacity of the reticulorumen is 10 times greater. Therefore, in comparison with cattle, sheep have to eat more as a percentage of BW, have higher passage rates and lower digestibility of fiber, have greater ability to select digestible feeds, are more negatively affected in their intake by forage fiber content and particle size, ruminate more finely and tend to digest better grains and pellets (Cannas et al. 2019).

Recent studies are scarce on the effects of pelleting hay on feed intake, digestibility, energy utilisation and performance in sheep. Ishaq et al. (2019) fed sheep wethers with loose and pelleted alfalfa hay. The animals were slightly lighter at the start of the trial than in our study. The feed intake was 17% higher with the pelleted diet. Apparent digestibility of dry matter did not differ significantly, but the NDF digestibility was lower for the pellet (26.7%) than the hay (34.9%) diet. The average daily gain was 0.084 vs 0.240 kg d^{-1} for the hay and pellet diets, respectively. In comparison, positive effects of pelleting on ad lib intake were over 50% in trials HT-85 and HT-87 and 34% in trial VB-05. The decrease in in vivo DM digestibility due to pelleting was in the range of 4 to 12 % in studies HT-85 and HT-87, greater at the higher feeding levels. The positive response in growth to pelleting in the study of Ishaq et al. (2019) was somewhat greater than in our studies, due to more positive effects of pelleting on feed conversion.

Some recent studies on the effect of pelleting feed for growing sheep have dealt with total mixed rations with very little or no forage (Zhong et al. 2018, Zhang et al. 2019, Li et al. 2021). There seems to be a renewed interest for using pelleted feeds for small ruminants, but for somewhat different reasons than in Iceland in the past, when forage was pelleted to make it possible to achieve high growth rates or milk yields, with domestically grown forage as the sole or major feed ingredient.

Total mixed rations (TMR) are used for growing lambs in some production systems. Expected advantages of pelleted over un-pelleted TMR are elimination of feed sorting and more uniform nutrient intake. Pelleting also makes it easier to include some less palatable by-products (Beigh et al. 2017). Pelleting also reduces feed volume and cost of transportation (Adesogan et al. 2019). Recent studies with total mixed rations with very little or no forage for growing sheep have shown that pelleted feed increased feed intake and average daily gain, had little or no effect on nutrient total tract digestibility and feed conversion ratio, and in general had positive effects on rumen fermentation, compared to un-pelleted feed (Zhong et al. 2018, Zhang et al. 2019, Li et al. 2021). It must be kept in mind that the initial composition and preparation of these feeds before pelleting is very different from forage-dominant diets like those in our study and the older studies discussed above. Incorporating this knowledge, however, broadens our perspective on the possible use of pelleted feeds for sheep in the future. In the last decades, there have been considerable developments in the forage and cereal species and varieties available for growing in Iceland. At the same time the Icelandic sheep have been bred towards more efficient growth. Likely, there will be interest in exploring new possibilities in pelleting technology and in the use of domestic, renewable energy sources. Hopefully, new feeding trials will be conducted in the coming years with respect to all these developments.

Our results indicated that the poorer utilisation of energy at the level of digestion caused by pelleting was at least compensated by decreased losses of energy after digestion, i.e., as heat and methane, in accordance with findings by (Blaxter & Graham 1956) and later researchers. Neither of these two energy losses were measured separately, but that is an obvious task for future studies due to the interest in decreasing methane production from rumen fermentation. Zhao et al. (2016) fed one-year old hoggets on fresh, ensiled, or pelleted ryegrass ad lib with no concentrate supplementation. Feed intake of pelleted ryegrass was around 50% higher than on the fresh or ensiled, and dry matter digestibility dropped to 59% compared to over 81-82% for the fresh or ensiled ryegrasses. Methane production per kg intake decreased by pelleting, but not as a proportion of digested energy. Theoretically that ratio could also decrease if pelleting resulted in changes in the rumen fermentation pattern, with a higher ratio of propionate and a lower ratio of acetate and methane, which can be expected with faster digestion (Sveinbjörnsson et al. 2006). Such a change in fermentation pattern because of pelleting was observed in the studies of Zhong et al. (2018) and Zhang et al. (2019).

The results reported here are valuable for future improvements of energy evaluation for sheep in Iceland (Sveinbjörnsson & Ólafsson 1999), as they give indications of the accuracy of the current predictions. It seems that the current system either overpredicts the feed or underpredicts the animal requirements, or both. Much better agreement was found between actual and predicted lamb growth performance when feed energy values were calculated from in vivo digestibility (Figure 2b) compared to in vitro digestibility (Figure 2a), indicating at least that sheep energy evaluation could benefit from accounting for the effect of feeding level and passage rate on actual digestion, as done in cattle feed evaluation (Volden & Larsen 2011).

CONCLUSIONS

Pelleting is an efficient way of making hay of variable digestibility a more productive feed for growing lambs. Pelleting increases feed intake and decreases digestibility, more for the poorer quality hay. Digestible energy is more efficiently transferred into net energy when the hay is pelleted, and this counterbalances the lowered digestibility with respect to forage utilisation.

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