Particle size distribution of forages and mixed rations, and their relationship with ration variability and performance of UK dairy herds

by Tayyab, U., Wilkinson, R.G., Reynolds, C.K. and Sinclair, L.A.

Harper Adams University

1 **Particle size distribution of forages and mixed rations, and their**

2 **relationship with ration variability and performance of UK dairy herds**

3 Usama Tayyab[a], Robert G. Wilkinson[a], Christopher K Reynolds[b], Liam A.

4 Sinclair[a*]

5

6 [a]Department of Animal Production, Welfare and Veterinary Sciences, Harper

7 Adams University, Edgmond, Newport, Shropshire, TF10 8NB, UK.

8 [b]School of Agriculture, Policy and Development, University of Reading, PO Box

9 237, Earley Gate, Reading, RG6 6AR, Berkshire, UK.

10

11 U. Tayyab: utayyab@harper-adams.ac.uk

12 R. G. Wilkinson: rgwilkinson@harper-adams.ac.uk

13 C. K. Reynolds: c.k.reynolds@reading.ac.uk

14 L. A. Sinclair: lsinclair@harper-adams.ac.uk

15

16

17

18 *Corresponding author. Liam A. Sinclair

19 *E-mail address*: lsinclair@harper-adams.ac.uk

20   ABSTRACT

21   The particle size of the ration has been proposed as a key factor, along with its

22   fibre and non-forage carbohydrate concentration, to ensure healthy rumen

23   function and optimal performance of dairy cows. The current particle size

24   distribution recommendations for forages and rations are primarily based on

25   lucerne-haylage and maize silage (MS) and may not be suitable for the wetter

26   grass silage (GS) based rations typically fed in Northern Europe. In order to

27   characterize the particle size distribution of forages and rations in the UK, fifty

28   commercial dairy herds feeding a range of GS and MS based rations were

29   sampled during the winter of 2015/2016. The particle size distribution of the fresh

30   forages and mixed rations (MR; total and partial mixed rations) were analysed

31   using a modified Penn State Particle Separator with six screens of hole size 60,

32   44, 26.9, 19, 8, and 4 mm. The fresh MR was collected at 5-equally-spaced

33   locations along the length of the feed-face for each herd within 5-min of feeding

34   to determine the consistency of ration mixing, and again from the same locations

35   4h post-feeding. Grass silage was the main forage fed on 50 herds, with 80.3%

36   of the dry matter (DM) being retained above the 19 mm sieve, which is

37   considerably higher than the North-American recommendations for lucerne-

38   haylage. The particle size distribution of MS followed the general

39   recommendations for North American forages, however, the 8-19 mm fraction

40   was higher and the <4 mm lower. The >60 mm fraction of the MR had the lowest

41   (0.1% DM) DM retention, and the 8-19 mm fraction the highest (34.9% DM). The

42   MR had a higher proportion of particles retained on the 26.9 mm sieve when GS

43   was the sole forage. Fifty eight % of herds were considered to have either

44   moderately or poorly mixed rations, whilst 66% had evidence of diet selection

2

45 (either preferential consumption or selective refusals). Particle size of the MR

46 accounted for 33% of the variance in the milk fat content and 12% of milk yield.

47 In conclusion, the particle size distribution of the GS and MR fed on UK dairy

48 herds is different from the current recommendations, suggesting that the particle

49 size of UK dairy rations is too long or new guidelines using additional sieves with

50 larger pore sizes are required. There is also a high proportion of herds with poor

51 mixing and/or evidence of diet selection.

52

53 *Key words*:

54 Dairy cows, ration variability, diet selection, particle size distribution

55

56 **1. Introduction**

57 Feeding dairy cows with a mixed ration (MR; either total or partial mixed ration)

58 is an effective way to provide a homogeneous and balanced diet throughout the

59 day (Coppock et al., 1981). The composition of MR can vary considerably but

60 ryegrass (GS) and maize silages (MS) are the main forages used in the MR fed

61 to dairy herds in Northern Europe (Johansen et al., 2018; March et al., 2014). In

62 order to maintain animal performance and promote a healthy rumen function the

63 inclusion of forages with an adequate particle size and dietary concentration of

64 non-forage carbohydrate (fibre) in the MR are required (Zebeli et al., 2012). The

65 physically effectiveness of a ration has been proposed as the product of the

66 particle size multiplied by its neutral detergent fibre (NDF) content, defined as

67 physically effective fibre (*peNDF*; Mertens, 1997). Achieving the correct particle

68 size and *peNDF* in a ration can enhance rumen function leading to an increase

69 in the production of rumen microbes, more efficient degradation of fibre and

70 increased milk fat content (De Brabander et al., 1999; Zebeli et al., 2012). A short

71 forage particle size is associated with improved compaction in the bunker and

72 can result in reduced aerobic spoilage at feed out (McDonald et al., 1991) and

73 may increase dry matter (DM) intake, due to reduced rumen fill and increased

74 fibre digestibility (Thomson et al., 2017). However, too short a forage particle

75 length can increase the rate of volatile fatty acid production in the rumen, reduce

76 rumination time, and decrease the production of saliva (Tafaj et al., 2007), with

77 the consequence of inhibiting cellulolytic bacteria activity and increasing the risk

78 of sub-acute ruminal acidosis (SARA; Tafaj et al., 2007). In a review of the

79 literature, Zebeli et al. (2012) concluded that too short a particle size (and

80 *peNDF),* increases the passage rate of digesta and rate of fibre degradation due

81 to a higher surface area for microbial attachment. In contrast, too long a forage

82 particle size may promote ration sorting and result in some cows receiving excess

83 concentrates and others insufficient (Kononoff and Heinrichs, 2003).

84 The estimation of the particle size of forages and MR is problematic, and various

85 methods have been proposed to characterise feed particle distribution using

86 different sieving techniques, with no universally accepted standard. Maulfair and

87 Heinrichs (2012) concluded that the Penn State Particle Separator was the most

88 useful method and proposed dietary guidelines for use on-farm. These

89 recommendations are primarily based on North American rations that consist of

90 MS and lucerne haylage (Eastridge, 2006), and may therefore not be suitable for

91 the typically wetter (e.g. less than 30% DM) MS and GS commonly fed in Northern

92 Europe (Møller et al., 2000).

93 Heinrichs et al. (1999) reported that processing by the mixer wagon prior to

94 feeding can also have a large effect on the consistency of the mix, and affect the

95 particle size and *peNDF* concentration of the ration subsequently consumed.

96 Mixing protocols have been shown to affect feed intake and milk yield, particularly

97 in rations containing longer chop lengths (Humphries et al., 2010; Maulfair and

98 Henrichs 2010). Consideration should therefore also be given to the effect of

99 particle size and consistency of mixing on the degree of diet selection by dairy

100 cows.

101 The primary objective of the present study was to characterise the particle size

102 distribution and *peNDF* content of GS, MS and MR fed on UK dairy herds using

103 a modified Penn State Particle Separator, and to compare the observed particle

104 size distribution with current guidelines. The secondary objective of the study was

105 to evaluate the consistency of mixing of MR and extent of sorting of GS and

106 GS/MS based MR, and to determine the relationship between particle size and

107 cow performance on UK dairy herds.

108

109 **2. Material and methods**

110 *2.1. Herd characteristics*

111 Fifty commercial dairy herds located throughout the UK (32 in the Midlands of

112 England, 9 in the South of England and 9 in Southwest Scotland) that were

113 feeding GS and/or MS were visited between January and June, 2016. The herds

114 were randomly selected from a database supplied by the Agricultural and

115 Horticultural Development Board, the levy body covering England, Scotland and

116 Wales, with the provision that they were using a MR (partial or total) feeding

117 system and had a high yielding group that contained at least 50 cows. Herds were

118 enrolled onto the study through an initial telephone contact and questionnaire

119 survey to determine suitability and willingness to participate. On the day of the

5

120   visit a second questionnaire was completed to collect details of herd

121   characteristics, performance levels and frequencies of fresh feed delivery, feed

122   push up and orts removal. In addition, feeding space per cow, feed mixer make

123   and model, forage harvester make and model, and mixing protocol were

124   recorded. The ingredient composition of MR fed to the target group and the mean

125   concentrate fed in the parlour was also recorded.

126   Out of the 50 herds, 50 fed GS, with 34 using MS in the MR. Other sources of

127   forage being fed were; whole-crop wheat (19), wheat straw (15), fodder beet (5),

128   grass haylage (2), whole-crop triticale (1), whole-crop barley (1), lucerne (1), pea

129   silage (1) and oat silage (1). Forty-four of the herds had an all year around calving

130   pattern, 4 were autumn block calving and 2 spring block calving. Holstein-Friesian

131   was the major breed on 36 herds, with the predominant breed on the remaining

132   herds being Ayrshire (2), Jersey (1), Brown Swiss (1), or (10) having a mixture of

133   Holstein with other breeds (Brown Swiss, New Zealand Friesian, and Jersey) or

134   crossbred. The main feeding system was total MR which was used on 28 herds,

135   while the remaining 22 herds fed a partial MR with additional concentrate fed in

136   the milking parlour. Twenty-four herds used a "tub" type mixer wagon, 18 a

137   "barrel" type, 7 an "auger" design (vertical or horizontal) and one used a forage

138   box.

139   Total herd size ranged from 75 to 2220 animals, with a mean of 354 (Table 1).

140   The number of lactating cows ranged from 67 to 1770 cows/herd, with a mean

141   and median of 310 and 277, respectively. The annual milk yield ranged from 6000

142   to 12500 kg/cow, with a mean of 9199 kg/cow (median = 9200). Annual energy

143   corrected milk yield (corrected for milk fat and protein; Sjaunja et al., 1991)

144   ranged from 7248 to 13209 kg/cow, with a mean of 10011 kg/cow. All herds

145 delivered fresh feed either once or twice daily, with a mean of 1.3 times/d. Of the

146 50 herds, 20 were feeding the MR in a trough where there was no push up the

147 feed. The average frequency of feed push up in the remaining 30 herds was 4.7

148 times/d. The mean orts removal frequency was 4.4 times/wk, with a range from

149 0.25 (monthly) to 7 (daily) times/wk. Feed space per cow ranged from 0.30 to

150 0.76 m/cow, with a mean of 0.56 m/cow. Length of feed mixing was either

151 manually recorded or provided by the farmer, and ranged from 5 to 60 min. The

152 number of chews per bolus was manually counted for three full bouts for 10 cows

153 randomly selected from the feeding group sampled (Kononoff et al., 2002).

154

155 *2.2. Determination of particle size and peNDF distribution of forages and MR*

156 Where more than one feeding group was present, data were collected from the

157 high yielding group in each herd (n = 40). Where feed was delivered more than

158 once (n = 15), the first (morning) feed was sampled. The feed face of the high

159 yielding group of cows (or all cows if no subdivision was present) was divided into

160 five equal sections to determine the consistency of mixing (Sova et al., 2014).

161 Within each feed face section, a 30 cm × 30 cm quadrat was randomly placed

162 over the MR within 5 mins of fresh feed-out, and all material removed and

163 thoroughly mixed by hand (0hMR; Endres and Espejo, 2010). To determine the

164 level of diet selection (feed sorting), the MR was sampled using the quadrat from

165 the same locations along the feed fence again four hours post feeding (4hMR;

166 Leonardi et al., 2005). Prior to fresh feed delivery, refusals, where available, were

167 also sampled (n = 33).

168 The particle size distribution of the forage (GS and MS) and MR samples were

169 analysed on both a fresh and dried basis. A modified Penn State Particle

170   Separator with four screens of 26.9, 19, 8, and 4 mm was used to determine the

171   particle size of GS and GS/MS based MR, and three screens of 19, 8 and 4 mm

172   for MS according to the manual shaking procedure described by Kononoff et al.

173   (2003). Perennial ryegrass (*Lolium perenne*) and MS (*Zea mays* L.) were

174   sampled from first, second or third cut GS and MS silage bunkers as described

175   by Sinclair (2006) and the particle size measured using the modified Penn State

176   Particle Separator described above. The particle size distribution (%) was

177   calculated by dividing the weight of each fraction by the sum of all fractions and

178   multiplying by 100.

179   The on-farm particle size distribution analysis using one additional Penn State

180   Particle Separator sieve screen (26.9 mm) was found to be inadequate to

181   accurately determine the geometric mean particle size (X_m) of GS and GS based

182   MR. Consequently, two larger sieve screens of size 44 and 60 mm were used to

183   reanalyse particle size of 0hMR and GS using frozen and defrosted samples. The

184   frozen samples were thawed at room temperature for 6h prior to analysis.

185

186   *2.3. Chemical analysis*

187   The DM content (AOAC, 2012; 988.05) of each fraction of 0hMR, 4hMR, refusals,

188   GS and MS for each herd was determined by oven drying at 105°C to constant

189   weight. Forage and MR samples were then milled in a hammer mill (Crompton

190   Control Series 2000, Wakefield West Yorkshire UK) fitted with a 1 mm screen.

191   The crude protein (988.05; Dumas method [N × 6.25]), ash (942.05; at 550°C for

192   6 h) and ether extract (920.39) was analysed as described by AOAC (2012). The

193   NDF (using sodium sulphite and heat stable amylase, and expressed residual of

194   ash) and acid detergent fibre (ADF) content was analysed according to Van Soest

195   et al. (1991). The starch content of the 0hMR was analysed by Trouw Nutrition

196   (Blenheim House, Blenheim Road, Ashbourne, Derbyshire, UK) using the

197   procedure described by McCleary et al. (1997).

198

199   *2.4. Calculations and statistical analysis*

200   Energy corrected milk yield (kg) was calculated as: milk yield (kg) × [(38.3 × fat

201   (g/kg) + 24.2 × protein (g/kg) + 15.71 × lactose (g/kg) + 20.7)/3,140], as described

202   by Sjaunja et al. (1991). The geometric mean particle size (X_m) was calculated

203   using the method described by ANSI (1992). The physical effectiveness factor

204   (*pef*) was determined as the DM proportion of particles longer than 8 mm

205   (*pef$_{>8mm}$*) or 4 mm (*pef$_{>4mm}$*, Lammers et al., 1996; Maulfair and Heinrichs, 2010).

206   The *peNDF$_{>4mm}$* was calculated by multiplying the NDF content (% DM) of the MR

207   by the *pef$_{>4mm}$*, and *peNDF$_{>8mm}$* by multiplying the NDF content (% DM) of the MR

208   by the *pef$_{>8mm}$* (Lammers et al., 1996; Mertens, 1997).

209   The consistency of ration mixing of each herd was calculated using the co-

210   efficient of variation (CV%) of each particle size fraction of the 0hMR (Buckmaster

211   et al., 2014; Oelberg and Stone, 2014; Sova et al., 2014), with a CV of >5%

212   considered significant (Silva-del-Rio and Castillo, 2012). The CV of each fraction

213   was weighted for the respective percentage particle size distribution and then the

214   corrected CV summed. Herd-level diet selection was calculated for each fraction

215   by dividing the proportion (DM basis) at 0hMR by the corresponding proportion

216   at 4hMR and refusals, and presented as a percentage. A sorting value of 100%

217   indicated no sorting, <100% indicated preferential consumption, and >100%

218   indicated selective refusal.

219   All data were summarised by herd and tested for normality using the general

220   descriptive statistics component of GenStat 17.1 ® (VSN International Ltd.,

221   Oxford, UK). Associations between measures of productivity (energy corrected

222   milk yield, milk fat g/kg, milk protein g/kg), feeding management and ration

223   characteristics were analysed using a standard linear model (i.e. ANOVA) with

224   forage source and shaking technique as fixed effects and herds and location as

225   random effects. A linear regression model was used to determine the association

226   between X_m and energy corrected milk yield and milk fat using GenStat 17.1 ®

227   (VSN International Ltd., Oxford, UK). For multiple comparisons, all fractions of

228   the mixed ration were analysed by general ANOVA followed by a Tukey test, with

229   the significant level set at $P < 0.05$.

230

231   **3. Results**

232   *3.1. Forage proximate and physical characteristics*

233   The mean DM of the GS was 23 g/kg lower ($P = 0.022$) and the CP 54 g/kg DM

234   higher than the MS (Table 2). The NDF and ADF content were also 65 and 64

235   g/kg DM higher in the GS than the MS ($P < 0.001$). The highest % DM retention

236   of GS was the 26.9-44 mm fraction (51.6%, $P < 0.001$), with the majority of the

237   DM (80.3%) being longer than 19 mm. In contrast, the highest retention of DM for

238   MS was between 8-19 mm (73.2%, $P < 0.001$). The X_m, *peNDF$_{>4mm}$* and

239   *peNDF$_{>8mm}$* content was higher ($P < 0.001$) in GS than MS (mean values of 42.6

240   and 10.5 mm, 48 and 40%, and 47 and 34% for X_m, *peNDF$_{>4mm}$* and *peNDF$_{>8mm}$*

241   for GS and MS respectively).

242

243 *3.2. Mixed ration proximate and physical characteristics*

244 The mean forage to concentrate ratio across the 50 herds was 77:23 on a fresh

245 weight basis, and 57:43 on a DM basis, with a GS to MS ratio on the 34 herds

246 that fed both forages of 50:50 (fresh weight basis) or 48:52 (DM basis; Table 3).

247 The DM concentration of the MR ranged from 213 to 544 g/kg, with a mean value

248 of 373 g/kg across the 50 herds, whilst the mean CP ranged from 116 to 205 g/kg

249 DM, with a mean value of 160 g/kg DM. The mean and median NDF

250 concentration of the MR was 391 and 381 g/kg DM respectively. For the MR, the

251 lowest proportion of DM was retained on the 60 mm fraction ($P < 0.001$), with the

252 8-19 mm fraction having the highest proportion ($P < 0.001$), and there was no

253 difference ($P > 0.05$) between the 44-60 and 19-26.9 mm fractions. The

254 *peNDF$_{>4mm}$* concentration of the MR ranged from 22 to 47% with a mean of 33%,

255 and the mean *peNDF$_{>8mm}$* was 73%. The mean X_m of the MR was 19.5 mm,

256 ranging from 6.2 to 44.9 mm. The starch concentration of MR ranged from 63 to

257 237 g/kg DM with a mean value of 138 g/kg DM. The mean DM of the 0h, 4h and

258 refusals did not differ ($P = 0.10$) between sampling times, and the DM

259 concentration of the various fractions of MR did not change over time ($P > 0.05$;

260 data not shown).

261 Herds that fed GS as the main forage had a higher ($P < 0.01$) proportion of the

262 DM retained on the 26.9-44 mm fraction of the 0hMR compared to those that

263 used a mixture of GS and MS (Table 4). In contrast, herds that used a mixture of

264 both forages had a higher ($P < 0.01$) proportion of the DM retained on the 8-19

265 mm fraction. The type of mixer wagon (barrel, tub or auger) had no effect ($P >$

266 0.05) on the particle size distribution of any fraction of the 0hMR (data not shown).

267 When the partial or total MR were considered separately, the proportion of longer

268 fractions (26.9-44 and 44-60 mm) was higher ($P < 0.05$) when in the partial MR,

269 while the shorter fractions (8-19, 4-8 and <4 mm) were highest ($P < 0.05$) when

270 fed as a total MR (Supplementary Table S1).

271

272 *3.3. Variability in mixed ration mixing*

273 The coefficient of variation of mixing of MR was highest for the 19-26.9 and >26.9

274 mm fractions at 15 and 13.7% respectively, while the minimum CV of 6.4% was

275 for the 8-19 mm fraction (Table 5). The type of wagon mixer, forage source, total

276 MR or partial MR, and X_m had no effect ($P > 0.05$) on ration variability across all

277 five fractions (data not shown).

278

279 *3.4. Particle size distribution of mixed rations post-feeding and diet selection*

280 Diet selection calculated between 0-4h, 4-24h and 0-24h, demonstrated that

281 there was selective refusal of the >26.9 and 19-26.9 mm fractions and a

282 preferential consumption of the 8-19, 4-8 and <4 mm fractions between 0-24h

283 period (Table 6), although there was considerable variation between herds.

284 Sorting activity calculated between 0 and 4h showed preferential consumption (P

285 < 0.001) for the 4-8 and 8-19 mm fraction of the MR while the >26.9, 19-26.9 and

286 <4 mm fractions were selectively refused. The inclusion of whole-crop wheat (n

287 = 19) and straw (n = 15), the mixer wagon type or X_m had no effect ($P > 0.05$) on

288 the level of feed sorting (data not shown).

289

290 *3.5. Association between particle size and production*

291 There was a positive relationship ($R^2 = 0.33$; $P = 0.004$) between X_m and mean

292 milk fat content (g/kg) across all herds (Figure 1). The relationship was improved

12

293   when Holstein-Friesian and Holstein-Friesian crosses were analysed separately

294   (R^2 = 0.36; P < 0.001), with the R^2 being highest when Holstein-Friesian herds

295   were analysed alone, with almost 50% of the variation in milk fat content between

296   herds being accounted for by X_m (R^2 = 0.47; P < 0.001). In contrast, there was a

297   negative relationship between X_m and energy corrected milk across the 50 dairy

298   herds, accounting for 16% of the variation (P < 0.001).

299

300   *3.6. Fresh vs dried particle size distribution*

301   When dried prior to separation there was a difference in particle size distribution,

302   with less long material and more short material than when measured fresh and

303   then dried (Table 7 and Supplementary Table S2). For GS the >26.9 mm fraction

304   decreased (P < 0.001), while the 8-19, 4-8 and the <4 mm fractions increased (P

305   < 0.001) when analysed in a dried form. Similarly, the 4-8 and <4 mm fractions of

306   the MS increased (P < 0.001) when analysed in a dried compared to a wet form.

307   For the MR, the proportion of the >26.9 mm decreased (P < 0.001), while the

308   proportion of the 4-8 and the <4 mm fractions increased (P < 0.01) when analysed

309   in a dried form compared to fresh and then dried.

310

311   **4. Discussion**

312   *4.1. Herd characteristics and proximate analysis*

313   The mean annual milk yield and herd size recorded in the current study were

314   higher than the values reported for the UK (yield of 8180 kg and 143 cows/ herd,

315   respectively; AHDB, 2016). This difference may be due in part to the selection

316   criteria for the current study, with all herds recruited feeding MR and using GS,

317   MS or a mixture as the main forage source. As a consequence, spring calving,

318   grazed grass based herds that have a lower mean milk yield (AHDB, 2016; Garcia

319   and Holmes, 1999) were not used, although the trend in the UK is for more

320   continuous housing, indoor feeding rather than grazing (March et al., 2014).

321   The MS being fed in the current study had a lower DM content at 300 g/kg

322   compared to the 395 g/kg reported by Lammers et al. (1996) in the northeast of

323   the United States of America (USA). The nutrient composition of the GS used in

324   the current study was, however, typical of European ryegrass silage (Møller et

325   al., 2000), with a mean CP of 136 g/kg DM and NDF of 492 g/kg DM. The mean

326   forage to concentrate ratio of the MR in the current study (57:43 DM basis) was

327   higher than that reported for 50 herds in Minnesota (52:48, Endres and Espejo,

328   2010). A higher forage to concentrate ratio is more likely to maintain an efficient

329   rumen function and should minimise the risk of SARA (Zebeli et al., 2012).

330   However, twenty four out of the 50 herds fed a lower proportion of forage in the

331   MR than the minimum of 56% proposed by Zebeli et al. (2012), and may

332   subsequently have been at risk of SARA.

333   The average DM of the MR in the current study of 373 g/kg was lower than that

334   reported by Eastridge (2006) and Sova et al. (2013) for typical North American

335   rations. In similar cross-sectional studies, Sova et al. (2013) reported a mean total

336   MR DM of 477 g/kg in 22 Canadian herds, while Endres and Espejo (2010)

337   reported a mean of 523 g/kg DM in the total MR of 50 herds in Minnesota, USA.

338   Rations with a high DM content may increase DM intake, but may also encourage

339   cows to sort (Leonardi et al., 2005). The CP content of the MR in the current study

340   was also lower compared to that of 50 herds in the USA (175 g/kg DM; Endres

341   and Espejo, 2010) or 22 herds in Canada (165 g/kg DM; Sova et al., 2013). This

342   difference may be due to the greater use of concentrates and lower use of forages

343   in North American rations as reflected in the lower forage to concentrate ratio

344   (Endres and Espejo, 2010). The average NDF content of the MR in the current

345   study was approximately 90 g/kg DM higher than that reported in the USA (298

346   g/kg DM; Endres and Espejo, 2010) or Canadian rations (313 g/kg DM; Sova et

347   al., 2013). This was probably due to the greater use of forage in the current study,

348   especially GS, which has a higher NDF concentration than MS or lucerne haylage

349   (Hoffman et al., 1993), but may also be affected by maturity at harvesting which

350   increases NDF concentration (Dawson et al., 2002). The higher concentration of

351   NDF in the MR along with a sufficient particle size are associated with a more

352   efficient rumen function for fibre degrading microbiota by resisting a depression

353   in rumen pH (Zebeli et al., 2012). Similarly, the ADF content was approximately

354   50 g/kg DM higher in the current study compared to that fed in the USA (198 g/kg

355   DM; Endres and Espejo, 2010) or Canadian rations (205 g/kg DM; Sova et al.,

356   2013), but was typical of Northern European rations (Johansen et al., 2018).

357

358   *4.2. Ration physical characteristics*

359   The particle size distribution of MS followed the general guidelines suggested by

360   Heinrichs (2013) of 3-8% above 19 mm, 45 to 65% between 8-19 mm, 20 to 30%

361   between 4 and 8 mm, and <10% below 4 mm although the 8-19 mm fraction of

362   MS in the current study was higher than that reported by Maulfair et al. (2010).

363   This difference may be due to the higher moisture content of MS used in the UK

364   that promotes the adherence of shorter particles, but may also reduce sorting

365   (Leonardi et al., 2005). Overall, the particle size distribution of MS in the UK was

366   similar to the current guidelines for MS based on North America rations, and

367   consequently, there is little requirement for additional research or separate

368 recommendations for UK and northern European MS. Out of the 50 herds used

369 in the current study, the minimum % DM of GS retained on the >19 mm sieve

370 was 49%, considerably higher than the 10-20% guidelines for lucerne haylage in

371 the USA (Heinrichs, 2013). Feeding a longer particle size may result in a higher

372 rumen pH and avoid SARA, but is also associated with a reduction in feed intake

373 due to a greater rumen fill (Tafaj et al., 2007; Zebeli et al., 2012).

374 The mean particle size distribution of the 0hMR in the current study differed from

375 the guidelines based on North American rations (Heinrichs, 2013), with the long

376 (>19 mm) particle size distribution being 38%, approximately 50% higher than

377 that reported by Sova et al. (2013), DeVries et al. (2011) or Hosseinkhani et al.

378 (2008), and approximately 4 times higher than that reported by Heinrichs (2013),

379 Endres and Espejjo (2010), Miller-Cushon and DeVries (2009), or Heinrichs and

380 Kononoff, (1996) (Supplementary Table S3). The difference in particle size

381 distribution of MR in the current study reflected the high inclusion of GS that

382 contained a very long particle size (>19 mm = 80% DM, X_m = 42.6 mm). The use

383 of other forages (e.g. whole-crop wheat, wheat straw, fodder beet) in the MR in

384 the current study did not significantly affect the particle size distribution of the MR,

385 and supports that the high proportion of GS in the ration was the major factor

386 causing the differences. The higher proportion of the 26.9-44 and 8-19 mm

387 particle fractions in the MR may also be explained by the high moisture content,

388 as 4-8 and <4 mm particles may have adhered to longer particles (Leonardi et

389 al., 2005). However, the considerably longer particle size of GS than lucerne

390 haylage based MR suggests that either the particle size of UK dairy rations is too

391 long or the need for more specific particle size measurement methods and

392 distribution recommendations when wetter GS is the major forage in the MR.

393   When GS was the sole forage in the MR, rations had a higher proportion of the

394   26.9-44 and 44-60 mm fractions which may promote ration sorting (DeVries et

395   al., 2007), although in the current study there was no relationship between Xm

396   and degree of sorting after 4 or 24 h. The additional 26.9, 44 and 60 mm pore

397   size sieves used in the Penn State Particle Separator in the current study allowed

398   a more even distribution of particle size for GS and MR samples than the

399   traditional Penn State Particle Separator. However, as a very small proportion of

400   particles was retained on the 19-26.9 mm screen, a screen larger than 26.9 mm

401   may be more appropriate.

402

403   *4.3. Variability in ration mixing*

404   Feeding MR is an effective method to provide all the required nutrients to dairy

405   cows, and a properly mixed ration ensures a uniform delivery of all feed ingredient

406   to the animal (Coppock et al., 1981). Mixer wagons and mixing protocols can

407   however, influence particle size distribution and result in differences in feed intake

408   and milk yield, particularly for rations with longer chop lengths (Humphries et al.,

409   2010). In a survey of Iranian herds, Esmaeili et al. (2016) reported a high

410   variability (CV >10%) in particle size distribution of MR with the highest variation

411   recorded for the >19 mm fraction, a finding in agreement with the current study.

412   There were 42% of herds that had a CV ≤5% (indicating a well-mixed ration),

413   26% that had a CV of between 5-10% (moderately mixed), and 32% that had a

414   CV >10% (poorly mixed ration). There was no effect of mixer model on overall

415   ration variability across all herds. In contrast, Heinrichs et al. (1999) reported that

416   MR processing by the mixer wagon can have a significant effect on the ration

417 consistency, particle size and *peNDF* concentrations of the ration subsequently

418 consumed.

419

420 *4.4. Herd level diet selection*

421 Herd level diet selection was calculated as the proportional change in each

422 fraction of the MR over time post-feeding. Feed sorting activity is usually

423 associated with the preferential consumption of fine starch or protein rich particles

424 in the ration (DeVries et al., 2007). However, in the current study, there were

425 selective refusals for the >19 mm fraction and preferential consumption for the

426 <8 mm fraction. To more easily determine the variability of diet selection across

427 herds, the long fractions (>60, 44-60, 26.9-44 and 19-26.9 mm) were summed

428 (>19 mm), and the short (4-8 and <4 mm) fractions summed (<8 mm), while

429 assuming that a sorting value of 100% ± 5 indicated no sorting, >105% indicated

430 selective refusal and a sorting value of <95% indicates preferential consumption.

431 Of the 50 herds, 82% had either selective refusal or did not show preferential

432 consumption for the >19 mm fraction which may be associated with the inclusion

433 of long particles of GS. There was no sorting activity observed for the <8 mm

434 fraction in 46% of the herds. As discussed previously, this may have been due to

435 the comparatively high moisture content of the MR in the current study that

436 caused the cohesion of smaller particles to larger particles making it more difficult

437 to sort (Beauchemin, 1991; Fish and DeVries, 2012; Leonardi et al., 2005).

438

439 *4.5. Associative effects of particle size and production*

440 Several authors have reported a relationship between *peNDF* and milk

441 performance (Tafaj et al., 2007; Zebeli et al., 2012). In the current study there

442   was also a positive relationship between *peNDF$_{>4mm}$* or *peNDF$_{>8mm}$* and milk fat

443   content (R^2 = 0.14 and R^2 = 0.16; *P* < 0.01, respectively), but these were not as

444   strong as with X_m, although due to the nature of the data caution should be

445   exercised when interpreting the results. The positive relationship between X_m and

446   milk fat content, and the negative relationship with milk yield is in agreement with

447   De Brabander et al. (1999). A long fibrous particle size is associated with an

448   increase of acetic acid production in the rumen that can subsequently lead to a

449   higher milk fat content (Merten, 1997). Alternatively, a higher fibre ration may

450   increase rumen pH and reduce the ruminal production of *trans*-10, *cis*-12

451   conjugated linoleic acid that has been associated with milk fat reduction

452   (Harvatine and Bauman, 2011). Contrary to our findings, Tafaj et al. (2007)

453   reported no correlation between particle size and milk yield or milk components

454   and suggested that any effect of particle size on milk yield mainly depends on its

455   influence on DM intake, which was not measured in the current study.

456

457   *4.6. Comparison of fresh and dry separation*

458   Compared with when measured fresh, the particle size distribution of dried

459   forages and MR differed, with the proportion of longer fractions decreasing while

460   short fractions increased after drying of samples (Kononoff et al., 2003). This

461   difference may be attributed to the wetter forages and rations used resulting in

462   adherence of short particles to larger particles, or the physical reduction in particle

463   size due to the shaking when undertaken dry. It is therefore recommended to

464   partially or completely dry the forages and MR before analyses in order to

465   overcome the moisture variation (Heinrichs, 2013). However, this may not be a

466   practical way of measuring particle size of wetter forages and MR on-farm.

467

5. Conclusions

469 The ==particle size== distribution of GS and MR based on GS in UK dairy herds was

470 found to be considerably higher than current guidelines that are based on North

471 American forages and rations. This suggests that the ==particle size== of UK dairy

472 rations is either too long, or that new guidelines or methods of ==particle size==

473 evaluation for GS and GS/MS based MR in Northern Europe are required. The

474 poor consistency of mixing and high degree of selection recorded on the majority

475 of herds is of concern, and further research into reasons for this variation and its

476 impact on cow performance is required. Finally, the high use of concentrates by

477 50% of the herds in the current study is a potential threat to SARA and reiterates

478 the need for more appropriate means of ==particle size== characterisation and

479 guidelines for wetter, GS based dairy rations, with further controlled studies

480 required to determine the optimal ==particle size== distribution of these rations.

481

6. References

AHDB, 2016. Statistics of UK dairy industry. http://dairy.ahdb.org.uk/market-information/#.V4zZrfkrKUk (accessed 18 July 2016).

ANSI, (American National Standards Institute), 1992. ANSI/ASAE S424.1 MAR1992 (R2012): Method of determining and expressing particle size of chopped forage materials by screening. St. Joseph, MI: ASAE.

AOAC. 2012. Official methods of analysis, 19th Ed. AOAC Int., Washington DC.

Beauchemin, K.A., 1991. Ingestion and mastication of feed by dairy cattle. Vet. Clin. N. Am-Food A. 7, 439-463.

Buckmaster, D.R., Wang, D., Wang, H., 2014. Assessing uniformity of total mixed rations. Appl. Eng. Agric. 30, 693-698.

Coppock, C.E., Bath, D.L., Harris, B., 1981. From feeding to feeding systems. J. Dairy Sci. 64, 1230-1249.

Dawson, L.E.R., Kirkland, R.M., Ferris, C.P., Steen, R.W.J., Kilpatrick, D.J., Gordon, F.J., 2002. The effect of stage of perennial ryegrass maturity at harvesting, fermentation characteristics and concentrate supplementation, on the quality and intake of grass silage by beef cattle. Grass and Forage Sci. 57, 255-267.

De Brabander, D.L., De Boever, J.L., Vanacker, J.M., Boucque, Ch.V., Botterman, S.M., 1999. Evaluation of physical structure in dairy cattle nutrition. In: Garnsworthy, P.C., Wiseman, J. (Eds.), Recent Advances in Animal Nutrition. Nottingham University Press, pp. 111–145.

DeVries, T.J., Beauchemin, K. A., Von Keyserlingk, M.A.G., 2007. Dietary forage concentration affects the feed sorting behavior of lactating dairy cows. J. Dairy Sci. 90, 5572-5579.

511 DeVries, T.J., Holtshausen, L., Oba, M., Beauchemin, K.A., 2011. Effect of parity

512 and stage of lactation on feed sorting behavior of lactating dairy cows. J.

513 Dairy Sci. 94, 4039-4045.

514 Eastridge, M.L., 2006. Major Advances in Applied Dairy Cattle Nutrition. J. Dairy

515 Sci. 89, 1311-1323.

516 Endres, M.I., Espejo, L.A., 2010. Feeding management and characteristics of

517 rations for high-producing dairy cows in freestall herds. J. Dairy Sci. 93, 822-

518 829.

519 Esmaeili, M., Khorvash, M., Ghorbani, G.R., Nasrollahi, S.M. and Saebi, M.,

520 2016. Variation of TMR particle size and physical characteristics in

521 commercial Iranian Holstein dairies and effects on eating behaviour,

522 chewing activity, and milk production. Livest. Sci. 191, 22-28.

523 Fish, J.A., DeVries, T.J., 2012. Short communication: Varying dietary dry matter

524 concentration through water addition; Effect on nutrient intake and sorting of

525 dairy cows in late lactation. J. Dairy Sci. 95, 850-855.

526 Garcia, S.C., Holmes, C.W., 1999. Effects of time of calving on the productivity

527 of pasture-based dairy systems: A review. New. Zeal. J. Agr. Res. 42, 347-

528 362.

529 Harvatine. K.J., Bauman, D.E., 2011. Characterization of the acute lactational

530 response to trans-10, cis-12 conjugated linoleic acid. J. Dairy Sci. 94, 6047-

531 6056.

532 Heinrichs, A.J., Buckmaster, D.R., Lammers, B.P., 1999. Processing, mixing and

533 particle-size reduction of forages for dairy cattle. J. Anim. Sci. 77, 180-186.

534 Heinrichs, J., 2013. The Penn State Particle Separator. Penn State University.

535 http://extension.psu.edu/animals/dairy/nutrition/forages/forage-quality-

536   physical/separator/extension_publication_file (accessed 19 July 2016).

537   Hoffman, P.C., Sievert, S.J., Shaver, R.D., Welch, D.A., Combs, D.K., 1993. In

538   situ dry matter, protein, and fiber degradation of perennial forages. J. Dairy

539   Sci. 76, 2632-2643.

540   Hosseinkhani, A., DeVries, T.J., Proudfoot, K.L., Valizadeh, R., Veira, D.M., von

541   Keyserlingk, M.A.G., 2008. The effects of feed bunk competition on the feed

542   sorting behavior of close-up dry cows. J. Dairy Sci. 91, 1115-1121.

543   Humphries, D.J., Beever, D.E., Reynolds, C.K., 2010. Adding straw to a total

544   mixed ration and the method of straw inclusion affects production and eating

545   behaviour of lactating dairy cows. Proceedings of the British Society of

546   Animal Science and Agricultural Research Forum, page 95.

547   Johansen, M., Lund, P., Weisbjerg, M.R., 2018. Feed intake and milk production

548   in dairy cows fed different grass and legume species: a meta-

549   analysis. Animal 12, 66-75.

550   Kononoff, P.J, Lehman, H., and Heinrichs, A., 2002. Technical note- A

551   comparison of methods used to measure eating and ruminating activity in

552   confined dairy cattle. J. Dairy Sci. 85, 1801-1803.

553   Kononoff, P.J., Heinrichs, A.J., Buckmaster, D.R., 2003. Modification of Penn

554   State forage and total mixed ration particle separator and the effects of

555   moisture content on its measurements. J. Dairy Sci. 86, 1858-1863.

556   Lammers, B.P., Buckmaster, D.R., Heinrichs, A.J., 1996. A simple method for the

557   analysis of particle sizes of forage and total mixed rations. J. Dairy Sci. 79,

558   922–928.

559   March, M.D., Haskell, M.J., Chagunda, M.G.G., Langford, F.M., Roberts, D.J.,

560   2014. Current trends in British dairy management regimens. J. Dairy Sci. 97,

561   7985-7994.

562   Maulfair, D.D., Heinrichs, A.J., 2010. Technical note: Evaluation of procedures

563   for analyzing ration sorting and rumen digesta particle size in dairy cows. J.

564   Dairy Sci. 93, 3784-3788.

565   Maulfair, D.D., Zanton, G.I., Fustini, M., Heinrichs, A.J., 2010. Effect of feed

566   sorting on chewing behavior, production, and rumen fermentation in lactating

567   dairy cows. J. Dairy Sci. 93, 4791-4803.

568   McCleary, B.V., Gibson, T.S., Mugford, D.C., 1997. Measurement of total starch

569   in cereal products by amyloglucosidase-a-amylase method: Collaborative

570   study. J. AOAC Int. 80, 571-579.

571   McDonald P., Henderson, A.R., Heron, S.J.E., 1991. The Biochemistry of Silage.

572   2nd edition. Chalcombe Publications, Marlow, Bucks, UK.

573   Mertens, D.R., 1997. Creating a system for meeting the fiber requirements of

574   dairy cows. J. Dairy Sci. 80, 1463-1481.

575   Miller-Cushon, E.K., DeVries, T.J., 2009. Effect of dietary dry matter

576   concentration on the sorting behavior of lactating dairy cows fed a total

577   mixed ration. J. Dairy Sci. 92, 3292-3298.

578   Møller, J., Thøgersen, R., Kjeldsen, A., Weisbjerg, M.R., Søegaard, K.,

579   Hvelplund, T., Børsting, C.F., 2000. Feedstuff tables. (English version) The

580   NationalCommittee on Cattle Husbandry, Report no. 91.

581   Oelberg, T.J., Stone, W., 2014. Monitoring total mixed rations and feed delivery

582   systems. Vet. Clin. N. Am-Food A. 30, 721-744.

583   Silva-del-Rio, N., Castillo, A.R., 2012. Degree of agreement between the ration

584   formulated and the ration fed on seven California dairies. J. Dairy Sci. 95,

585   (E. Suppl. 2):579. (Abstr.).

586   Sinclair, L.A., 2006. Effect of sample position within a clamp on the nutritive value

587   of fermented and urea-treated whole crop wheat. Proceedings of the British

588   Society of Animal Science, 44.

589   Sjaunja, L.O., Baevre, L., Junkkarinen, L., Pedersen, J., Setala, J., 1991.

590   Measurement of the total energy content of cow's milk and the energy value

591   of milk fat and milk protein. Eaap Public, 50, 52-155.

592   Sova, A.D., LeBlanc, S.J., McBride, B.W., DeVries, T.J., 2013. Associations

593   between herd-level feeding management practices, feed sorting, and milk

594   production in freestall dairy farms. J. Dairy Sci. 96, 4759-4770.

595   Sova, A.D., LeBlanc, S.J., McBride, B.W., DeVries, T.J., 2014. Accuracy and

596   precision of total mixed rations fed on commercial dairy farms. J Dairy

597   Sci. 97, 562-571.

598   Tafaj, M., Zebeli, Q., Baes, C., Steingass, H., Drochner, W., 2007. A meta-

599   analysis examining effects of particle size of total mixed rations on intake,

600   rumen digestion and milk production in high-yielding dairy cows in early

601   lactation. Anim. Feed Sci. Tech. 138, 137-161.

602   Thomson, A.L., Humphries, D.J., Jones, A.K., Reynolds, C.K., 2017 The effect

603   of varying proportion and chop length of lucerne silage in a maize silage-

604   based total mixed ration on diet digestibility and milk yield in dairy cattle.

605   Animal, 11, 2211-2219.

606   Van Soest P.J., Robertson J.B., Lewis B.A., 1991. Methods for dietary fiber,

607   neutral detergent fiber, and nonstarch polysaccharides in relation to animal

608   nutrition. J. Dairy Sci. 74, 3583-3597.

609   Yang, W.Z., Beauchemin, K.A., 2006. Physically effective fiber: Method of

610   determination and effects on chewing, ruminal acidosis, and digestion by

611   dairy cows. J. Dairy Sci. 89, 2618-2633.

612   Zebeli, Q., Aschenbach, J.R., Tafaj, M., Boghun, J., Ametaj, B.N., Drochner, W.,

613   2012. Review: Role of physically effective fiber and estimation of dietary

614   fiber adequacy in high-producing dairy cattle. J. Dairy Sci. 95, 1041-1056.

615   Figure captions

616

617   **Figure 1.** Relationship between mean particle size of MR (X_m, mm) and milk fat

618   (g/kg/herd) across 50 herds containing Holstein Friesian (HF; ●=36), Ayrshire

619   (▲=2), Jersey (+=1), Brown Swiss (■=1) and Holstein crossbred (HFX; ♦=10).

620

621   **Figure 2.** Relationship between mean particle size of MR (X_m, mm) and energy

622   corrected milk (ECM; Tyrrel and Reid, 1965) across 50 herds containing Holstein

623   Friesian (HF; ●=36), Ayrshire (▲=2), Jersey (+=1), Brown Swiss (■=1) and

624   Holstein crossbred (HFX; ♦=10).

Figure 1.

Figure 2.

All data: y = -0.1587x + 36.47
R² = 0.1609, P<0.001

HF data: y = -0.1192x + 36.69
R² = 0.1, P = 0.06

HF & HFX data: y = 0.136x + 36.37
R² = 0.1153, P = 0.021

Y-axis: ECM, kg/cow/day

X-axis: X_m of MR, mm
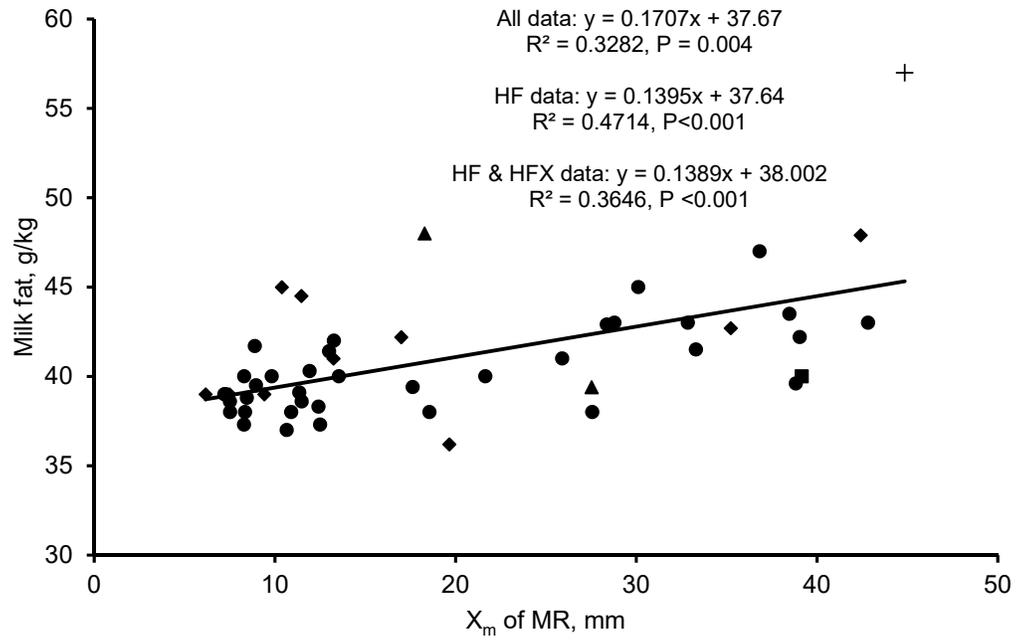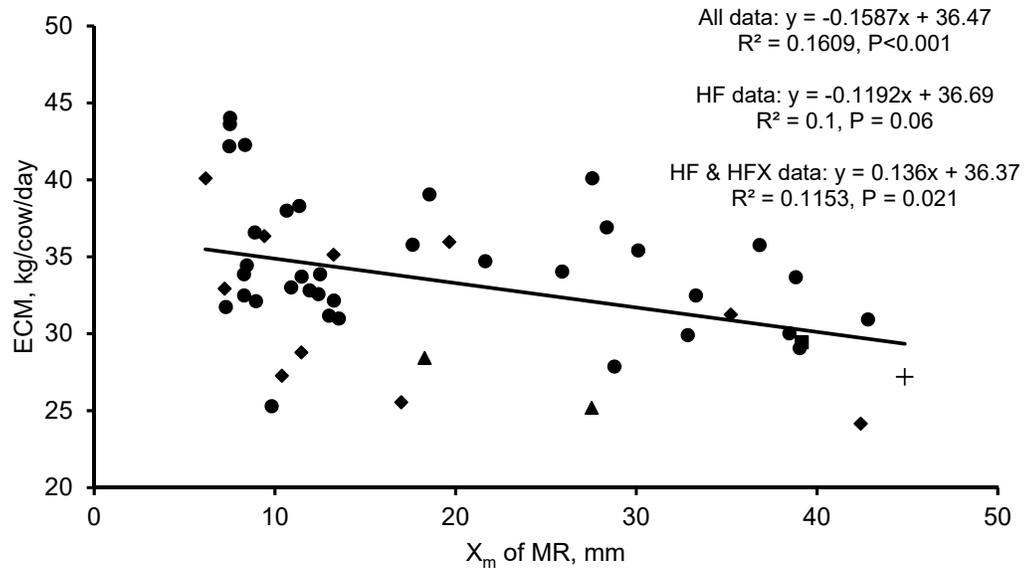
Table 1. Herd and feeding characteristics on 50 UK dairy herds.

	Mean	SD	Min	Max	Median
Herd size (n)	354	343.9	75	2220	277
Cows in milk (n)	310	282.3	67	1770	240
Milk yield (kg/cow/year)	9199	1583.2	6000	12500	9200
Milk fat (g/kg)	41.0	0.36	36.2	57.0	40.0
Milk protein (g/kg)	32.9	0.21	29.3	41.0	32.8
ECM yield (kg/cow/year)[1]	10011	1434.9	7248	13209	9891
Frequency of fresh feed delivery (n/d)	1.3	0.46	1	2	1.0
Frequency of feed push up (n/d)[2]	4.7	3.19	1	16	4.0
Frequency of refusals removal (n/wk)	4.4	2.75	0.25	7	5.5
Feed space per cow (m/cow)	0.56	0.098	0.30	0.76	0.61
Length of feed mixing (min/mix)	19	10.2	5	60	15
No. of chews/bolus	66	9.81	44	105	66

[1]Energy corrected milk.
[2]Herds feeding into a trough (n = 20) have been excluded.

Table 2. Mean chemical (g/kg DM ± SD) and physical characteristics (%DM ± SD) of grass (n = 50) and maize silage (n = 34) on 50 dairy herds.

Chemical composition	Grass silage			Maize silage			SED	P value
	Mean	Min	Max	Mean	Min	Max		
Dry matter (g/kg)	273 ± 46.1	205	390	300 ± 55.8	219	420	11.2	0.022
Organic matter	899 ± 20.0	854	945	961 ± 7.1	942	974	3.6	< 0.001
Ash	101 ± 20.0	55	146	39 ± 7.1	26	58	3.6	< 0.001
Crude protein	136 ± 26.0	81	184	82 ± 9.3	56	98	4.7	< 0.001
Neutral detergent fibre	492 ± 75.0	362	702	427 ± 74.1	276	559	16.8	< 0.001
Acid detergent fibre	331 ± 41.9	242	459	267 ± 44.8	176	347	9.7	< 0.001
Physical composition								
Fractions (mm)[1]								
>60	2.1 ± 5.12[a]	0	31.8	-	-	-	ND	ND
44-60	23.1 ± 13.38[c]	0	53.5	-	-	-	ND	ND
26.9-44	51.6 ± 14.01[d]	5.9	77.2	-	-	-	ND	ND
19-26.9	3.5 ± 3.29[a]	0.7	20.5	6.9 ± 4.55[a]	2.0	22.8	0.75	< 0.001
8-19	15.8 ± 10.01[b]	0.8	39.8	73.2 ± 8.75[d]	37.7	84.1	2.02	< 0.001
4-8	2.4 ± 1.44[a]	0.6	6.9	13.1 ± 5.02[c]	7.7	33.1	0.77	< 0.001
<4	1.6 ± 1.35[a]	0.1	6.0	6.8 ± 4.14[a]	1.4	18.8	0.64	< 0.001
$pef_{>4mm}$ (%)[2]	98 ± 1.5	93	100	93 ± 4.1	81	99	0.6	< 0.001
$peNDF_{>4mm}$ (%)	48 ± 7.0	36	66	40 ± 7.7	24	54	1.7	< 0.001
$pef_{>8mm}$ (%)[3]	96 ± 3.1	86	100	80 ± 8.0	48	90	1.3	< 0.001
$peNDF_{>8mm}$ (%)	47 ± 6.7	35	62	34 ± 7.7	19	48	1.6	< 0.001
X_m[4]	42.6 ± 5.63	17.5	53.9	10.6 ± 1.21	7.4	13.6	0.98	< 0.001

DM = dry matter, SD = standard deviation, SED = standard error of difference

[1]Grass silage was separated into 7 fractions; >60, 44-60, 26.9-44, 19-26.9, 8-19, 4-8 and <4 mm. Maize silage was separated into 4 fractions; >19, 8-19, 4-8 and <4 mm.

[a,b,c,d] Within each forage, different superscripts between fractions indicate a significant (P < 0.05) difference.

[2]Physical effective factor; % proportion of particles >4 mm.

[3]Physical effective factor; % proportion of particles >8 mm.

[4]Geometric mean particle size.

Table 3. Mean chemical composition and physical characteristics of mixed rations (MR) on 50 herds.

	Fresh basis	DM basis		
Forage (kg/cow/d)	40.5	12.2		
Concentrate (kg/cow/d)[1]	11.7	9.5		
Forage to concentrate ratio (F:C)[1]	77:23	57:43		
Grass to maize silage ratio (GS:MS)[2]	50:50	48:52		
Composition (g/kg DM ± SD)[1]	Mean	Min	Max	Median
Dry matter (g/kg)	373 ± 78.6	213	544	380
Organic matter	920 ± 11.5	883	944	922
Ash	80 ± 11.5	56	117	78
Crude protein	160 ± 18.9	116	205	162
Ether extract	28 ± 8.2	11	40	30
Starch	138 ± 44.1	63	237	139
Neutral detergent fibre	391 ± 59.3	290	507	381
Acid detergent fibre	249 ± 42.6	173	329	245
Physical composition (%DM ± SD)				
Fractions (mm)[3]				
>60	0.1 ± 0.29	0	1.4	0
44-60	7.3 ± 9.27	0	32.8	2.4
26.9-44	26.0 ± 15.10	1.6	75.9	24.7
19-26.9	4.4 ± 3.38	0.9	21.8	3.7
8-19	34.9 ± 13.31	3.5	67.8	34.9
4-8	11.8 ± 5.58	0.9	29.6	10.9
<4	15.5 ± 9.72	0.4	37.4	14.9
$pef_{>4mm}$ (%)[4]	85 ± 9.6	63	100	85
$peNDF_{>4mm}$ (%)	33 ± 6.8	22	47	33
$pef_{>8mm}$ (%)[5]	73 ± 12.9	44	99	70
$peNDF_{>8mm}$ (%)	29 ± 7.3	16	43	28
X_m[6]	19.5 ± 12.09	6.2	44.9	13.3

[1]Includes the concentrates offered in the parlour.
[2]Ratio of GS to MS in 34 herds, where both silages were fed.
[3]Rations were separated into 7 fractions; >60, 44-60, 26.9-44, 19-26.9, 8-19, 4-8 and <4 mm; SED = 2.72 and $P < 0.001$.
[4]Physical effective factor; % proportion of particles >4 mm.
[5]Physical effective factor; % proportion of particles >8 mm.
[6]Geometric mean particle size.

Table 4. Particle size distribution of mixed rations (0hMR) at feed out containing grass silage (16) and mixtures of grass and maize silage (34) on 50 herds.

Fractions[1] (mm)	Particle size distribution (%DM)		SED	*P* value
	GS	GS+MS		
>60	0.1	0.1	0.08	0.55
44-60	10.6	5.7	2.75	0.08
26.9-44	34.6	22.0	4.25	< 0.01
19-26.9	3.5	4.8	1.01	0.22
8-19	26.4	39.0	3.65	< 0.01
4-8	10.2	12.6	1.67	0.15
<4	14.6	15.9	2.97	0.68
X_m[2]	23.1	17.8	3.63	0.15

GS = grass silage, GS+MS= mixture of grass and maize silage, SED = standard error of difference

[1]Rations were separated into seven fractions; >60, 44-60, 26.9-44, 19-26.9, 8-19, 4-8 and <4 mm.

[2]Geomatic mean particle size.

Table 5. Within farm standard deviation (SD) and coefficient of variation (CV) of particle fractions of mixed ration at 5 points along feed face on 50 dairy herds.

Fractions[1] (mm)	Mean[2]	Standard deviation[3]			CV (%)[4]		
		Mean ± SD	Min	Max	Mean ± SD	Min	Max
>26.9	33.4	2.9 ± 2.28	0.1	10.8	13.7 ± 13.25	0.1	10.8
19-26.9	4.4	0.7 ± 1.16	0.1	7.7	15.0 ± 12.56	0.1	7.7
8-19	34.9	2.1 ± 1.60	0.0	7.9	7.3 ± 8.09	0.0	7.9
4-8	11.8	0.7 ± 0.53	0.1	2.9	6.4 ± 4.59	0.1	2.9
<4	15.5	1.1 ± 1.26	0.1	5.9	8.0 ± 7.43	0.1	5.9

[1]Ration was separated into five fractions; >26.9, 19-26.9, 8-19, 4-8 and <4 mm.
[2]Average particle size distribution of MR on 50 herds.
[3]SD of each fraction at 5 sampling points at each farm.
[4]CV = (SD of each fraction at 5 sampling points at each farm/ average value of each fraction) × 100.

Table 6. Group level sorting[1] (% ± SD) on 50 dairy herds.

Fractions[2] (mm)	Sorting		
	0-4h	4-24h[3]	0-24h[3]
>26.9	115 ± 59.5	158 ± 98.8	165 ± 113.0
19-26.9	101 ± 10.6	117 ± 47.8	106 ± 9.0
8-19	99 ± 28.0	92 ± 39.1	89 ± 32.4
4-8	99 ± 25.7	85 ± 32.5	83 ± 36.5
<4	103 ± 52.8	96 ± 143.7	93 ± 83.6

[1]Sorting was calculated for each fraction by dividing the proportion (DM basis) at 0hMR by the corresponding proportion at 4hMR and RefMR, and presented as a percentage. A sorting value of 100% indicated no sorting, <100% indicated preferential consumption, and >100% indicated selective refusal.

[2]Rations were separated into 5 fractions; >26.9, 19-26.9, 8-19, 4-8 and <4 mm.

[3]24h sorting activity was calculated across 33 herds, where refusals were available.

Table 7. Comparative particle size distribution of mixed rations (n = 50), grass silage (n = 50) and maize silage (n = 34) analysed by fresh and dry shaking on 50 dairy herds.

Sample	Fractions[1] (mm)	% Dry matter		SED	*P* value
		Fresh	Dry		
Grass silage	>26.9	78.7	45.7	3.15	< 0.001
	19-26.9	2.7	2.9	0.38	0.75
	8-19	14.3	34.4	2.16	< 0.001
	4-8	2.6	10.1	0.63	< 0.001
	<4	1.7	6.9	0.57	< 0.001
Maize silage	>19	6.9	4.3	0.87	0.004
	8-19	73.2	52.6	2.37	< 0.001
	4-8	13.1	28.8	1.53	< 0.001
	<4	6.8	14.3	1.28	< 0.001
Mixed ration	>26.9	32.8	16.2	4.08	< 0.001
	19-26.9	4.4	3.5	0.54	0.10
	8-19	35.6	38.0	2.58	0.35
	4-8	12.2	21.2	1.25	< 0.001
	<4	15.0	21.1	1.88	0.002

[1]MR and GS were separated into 5 fractions; >26.9, 19-26.9, 8-19, 4-8 and <4 mm. MS was separated into 4 fractions; >19, 8-19, 4-8 and <4 mm.