

Scotland's Rural College

## Soil compaction effects on grassland silage yields and soil structure under different levels of compaction over three years

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1 **Title:** Soil compaction effects on grassland silage yields and soil structure under different  
2 levels of compaction over three years.

3 **Authors:** P.R. Hargreaves, K.L. Baker, A. Graceson, S. Bonnett, B.C. Ball and J.M. Cloy

4 **Application Text Abstract:** Soil compaction has been estimated to be responsible for 33  
5 million ha of soil degradation in Europe, reducing crop yields, however there is limited data  
6 on grassland silage yields loss. This work aimed at studying the effect of increased animal  
7 trampling and mechanical (tractor) soil compaction on grassland silage mean dry matter  
8 (DM) yields and soil structure over a three year period at two UK sites. Results showed  
9 trampling and tractor compaction decreased mean DM yields over three years and by the  
10 third year DM yield for the trampled area was 11.4% less on the soil with greater clay  
11 content soil and 12.0% less on the more sandier soil than the no compaction control. DM  
12 yield for the tractor compaction, by the third year, was 14.5% less than no compaction DM  
13 yield, on both soil types. Compaction reduced N uptake, decreased drainage and increased  
14 water filled pore spaces (WFPS). Linear regression of visual evaluation of soil structure  
15 (VESS) scores and bulk densities provided evidence that VESS is an effective tool for  
16 detecting grassland compaction and would assist with the management of moderately  
17 compacted soils where deteriorate soil conditions may result in yield loss.

18 **Full Abstract:** Soil compaction has been estimated to be responsible for 33 million ha of  
19 soil degradation in Europe, reducing crop yields, however there is limited data on grassland  
20 silage yields loss. Extended grazing periods, increased size and weight of farm vehicles and  
21 more extreme weather have fostered concern over the consequences of grassland  
22 management on reduced grass yield and soil quality. This work aimed at studying the effect  
23 of increased animal trampling and mechanical (tractor) soil compaction on grassland silage  
24 mean dry matter (DM) yields and soil structure over a three year period at two UK sites.  
25 These sites were on two established perennial ryegrass fields with contrasting soil textures;  
26 an imperfectly drained silty clay loam in SW Scotland and a well drained sandy loam from

27 central England. Results showed trampling and tractor compaction decreased mean DM  
28 yields over three years and by the third year DM yield for the trampled area was 11.4% less  
29 on the soil with greater clay content soil and 12.0% less on the more sandier soil than the no  
30 compaction control. DM yield for the tractor compaction, by the third year, was 14.5% less  
31 than no compaction DM yield, on both soil types. Compaction treatments gave the greatest  
32 reductions for the first silage cut DM yields annually, for both soil types. The largest  
33 reductions (19.0% for trampling and 37.7% for tractor) were on the soil with the greater clay  
34 content in the second year, with the coolest start to the growing season. Compaction  
35 reduced N uptake, decreased drainage and increased water filled pore spaces (WFPS).  
36 Linear regression of visual evaluation of soil structure (VESS) scores and bulk densities  
37 provided evidence that VESS is an effective tool for detecting grassland compaction and  
38 would assist with the management of moderately compacted soils where deteriorate soil  
39 conditions may result in yield loss.

40 **Keywords:** Soil compaction, grassland, bulk density, yield, Visual Evaluation of Soil  
41 Structure

42

43 **1. Introduction:** Concerns about the structural damage of grassland soils by compaction have  
44 grown in recent years. Soil compaction has been estimated to be responsible for 33 million ha  
45 of soil degradation in Europe (Hamza and Anderson, 2003), with a more recent estimate that  
46 32% of European subsoils were compacted and 18% were moderately susceptible to  
47 compaction (Horn and Fleige, 2009).

48 The potential for soil compaction and soil structural damage increases with soil moisture, up  
49 to field capacity, the optimum point for compaction and corresponds to the soil plastic limit  
50 (Hamza and Anderson, 2005). Pressure on the soil surface forces the soil aggregates closer  
51 together, deforming the structure and reducing the soil porosity resulting in an increase in soil  
52 bulk density. In turn, this restricts the diffusion of oxygen (O<sub>2</sub>) and the hydraulic conductivity in

53 the soil (Arvidsson and Hakansson, 1991; Batey, 2009). The increase in soil bulk density as a  
54 result of compaction also has been shown to alter and reduce root growth (Tracy et al., 2011;  
55 Botta et al., 2006; Głab, 2013) and decrease the uptake of nutrients from the soil (Lipiec and  
56 Stępniewski, 1995; Arvidsson, 1999). These factors, in conjunction with increased soil  
57 moisture as a result of reduced drainage, can decrease the efficiency of the soil microbial  
58 population in the turnover of nutrients available to the crop (Cui and Holden, 2015). The effects  
59 of compaction on soil functions vary with soil type. Light sandy soils, due to their larger soil  
60 particles and larger pore size are less susceptible to compaction, even when moist, compared  
61 to silty clay loam soils with smaller particles and smaller pore size with a weaker structure  
62 that are therefore more compactible, especially when moist (Horn et al., 1995).

63 Soil compaction damage is becoming more common through the introduction of larger  
64 machinery (Gysi et al., 2000; Van den Akker and Schjønning, 2004). The more frequent  
65 occurrence of wetter weather conditions predicted, even during the summer months, in Europe  
66 (Christensen and Christensen, 2003), increases risks associated with soil structural damage  
67 through compaction.

68 Previous work has shown that compaction damage of soil under arable crops decreased crop  
69 yield of cereals (Radford et al, 2001), sugar beet (Koch et al, 2008) and forage maize (Neuens  
70 and Reheul, 2003) and increased the need for nitrogen (N) fertiliser to maintain the yields at  
71 pre-compaction levels (Soane and van Ouwerkerk, 1995).

72 The study of the effects of soil compaction on intensive grassland has not been as extensive  
73 as arable land (Douglas, 1997) or not based on temperate growing conditions (Balbuena et  
74 al, 2002). A recent visual survey of 300 grassland sites across England and Wales identified  
75 differing severities of structural damage with an estimated 10% of soils in poor condition  
76 (Defra, 2012; Newell-Price et al, 2013). This corresponded well with bulk density  
77 measurements that indicated 16% were badly compacted. However, if sites assessed as  
78 moderate soil condition, i.e. requiring management to alleviate the compaction problem, were  
79 considered, this resulted in approximately 70% of sites affected by soil structural damage.

80 This study also showed the suitability of visual evaluations of soil structure for quantifying  
81 structural damage to grasslands.

82 Two of the main causes of damage to grassland soils from compaction are trampling (Menneer  
83 et al., 2005; Thomas et al., 2008) by grazing animals and vehicle traffic (Batey, 2009). In recent  
84 years the more intensive and extended duration (i.e. February to October) of grazing in dairy  
85 farming (Kennedy et al., 2006) has encroached into periods when the soils are wetter and  
86 likely to be closer to field capacity (Defra, 2008), thus increasing the potential for intensively  
87 managed grassland to be damaged by soil compaction and potentially reduce yields through  
88 trampling (Herbin et al., 2011) and vehicle traffic. Quantifying yield loss from these two sources  
89 of compaction is important to help farmers in managing their soils to ensure they sustain  
90 maximum productivity.

91 The aims of this study were to investigate the effect of both animal trampling and vehicle  
92 compaction on grassland soil structure, yield reduction and grass sward quality of two  
93 contrasting soils (a coarse textured draining sandy soil and a finer textured, silty clay loam)  
94 in differing climates (both temperate but one cool and wet with the other warmer with less  
95 rainfall) over three consecutive years.

96

## 97 **2. Materials and Methods:**

### 98 2.1. Field experiment sites

99 The two sites were chosen to represent different climates and soil types within the UK with  
100 potentially contrasting responses to compaction. One site was located in the south west of  
101 Scotland (55°02'19"N, 3°36'06"W) (SRUC) and, although productive, was susceptible to  
102 poaching and compaction, particularly when wet. The field was an imperfectly drained silty,  
103 clay, loam of the Stirling soil series (30% clay, 14% sand and 55% silt) (Gleyic Cambisol,  
104 FAO, 2006) that overlies red sandstone parent material (pH 5.7, K and P medium to high)  
105 and had been sown as a perennial rye-grass sward (*Lolium perenne*) for 5 years prior to the

106 experiment starting. The second site was located on the campus farm of Harper Adams  
107 University (HAU), Shropshire, central England (52°46'53"N, 2°26'20"W) on a freely draining  
108 sandy loam (> 20% sand and < 18% clay) of the Arrow soil series (Eutric Cambisol, FAO,  
109 2006) with an underlying sandstone parent material (pH 7, K and P high). The field had  
110 supported a productive, sown perennial ryegrass sward for 3 years prior to the start of the  
111 experiment.

## 112 2.2. Experimental design and compaction treatments

113 The same randomised block experiment was established at each location and consisted of  
114 three replicate blocks (20 x 72m). Each block contained three replicate treatments (24 m x  
115 20 m) of i) cattle trampling compaction, ii) weighted tractor compaction and iii) a control of no  
116 compaction. The trampling compaction was achieved by 12 heifers (target weight of 550 kg)  
117 walking across each of the three replicate treatment areas for one hour, on two occasions,  
118 one week apart. Mechanical compaction was performed by driving a weighted tractor (10.5 t)  
119 over the treatment areas so the wheeling tracks covered the entire sward surface. This was  
120 based on the width of the area needing to be covered and the wheeling width of 1.7 m of the  
121 tractor. The tractor drove up the plot with the outside of the rear tyre corresponding to the  
122 plot edge then turning off the plot and returning with the rear tyre abutting the edge of the  
123 first wheeling. This process was repeated until the whole of the area was covered. The  
124 target compaction pressures of animal hoof and mechanical wheel were designed to be  
125 similar at ~250 kPa, to allow the influence of the mechanism of compaction to be  
126 distinguished from that of the compactive effort. The no compaction areas only had essential  
127 traffic for the management of the grass sward for three silage cuts (i.e. harvesting, fertiliser  
128 and slurry application). As the main treatment areas contained other sub-treatments,  
129 therefore smaller areas (4 m x 20 m) were used for sampling. The effects of compaction on  
130 yield were only considered in this study from the plots that had not had any further  
131 treatments. Soil measurements were taken from one half so not to disturb the yield taken

132 from the other half. The layout of the experimental plots is shown in the Supplementary  
133 Data.

134 The first compaction treatments were imposed in November 2011 at SRUC (i.e. the autumn  
135 before yield measurements) and February 2012 at HAU (i.e. the same year as yield  
136 measurements). These were repeated at a similar time each year for a further two years  
137 (Table 1).

138 Fertiliser was applied three times during the year (Table 1), once as an inorganic fertiliser  
139 (urea at 60 kg N ha<sup>-1</sup>) at the end of March, with slurry subsequently (at a rate of 30 m<sup>3</sup> ha<sup>-1</sup>;  
140 average N 63 kg ha<sup>-1</sup>; P 13 kg ha<sup>-1</sup>, K 49 kg ha<sup>-1</sup>) with a tractor, tanker and trailing shoe  
141 within two weeks of the first and second grass cuts.

142

## 143 2.3. Measurements

### 144 2.3.1. Bulk density and Water Filled Pore Space

145 At SRUC, bulk density and gravimetric moisture contents were measured (Robertson et al,  
146 1999) for all plots one week prior to application of any of the compaction treatments using  
147 cores sampled from metal rings (5 cm deep with a diameter of 7.3 cm) and then in October  
148 each year after before the subsequent compaction treatments were applied. Five samples  
149 for soil moisture, from each plot were taken during each sampling at the 0-10 cm and 10-20  
150 cm depths. Three samples were taken at four sampling depths 0-5 cm, 5-10 cm, 10-15 cm  
151 and 15-20 cm for bulk density. Bulk density samples from 0-10 cm and 10-20cm were taken  
152 at HAU prior to the start of the experiment but only to 0-10cm depth after application of the  
153 compaction treatments, as the drier, stony ground conditions prevented obtaining deeper  
154 cores.

155 The water filled pore space (WFPS) (%) values were calculated using bulk density and water  
156 content data (Robertson et al, 1999) for monthly soil samples taken at 0-10 cm and 10-20

157 cm depths where data was available, assuming a general particle density of  $2.65 \text{ g cm}^{-3}$   
158 (Blake and Hartge, 1986).

### 159 2.3.2. Visual Evaluation of Soil Structure (VESS)

160 Initial visual assessments of soil structure were made throughout the experiment, one week  
161 before the compaction treatments were applied, using the Visual Evaluation of Soil Structure  
162 (VESS) system (Ball et al, 2007). This involved digging out one intact block of soil (25 x 10 x  
163 15 cm) from each plot and scoring the structure for attributes of strength, porosity and  
164 aggregate morphology each sampling time. The VESS assessment was repeated within  
165 each treatment block after the initial compaction treatments were applied and again on all  
166 replicate treatments in October of 2012, 2013 and 2014, before further compaction  
167 treatments were applied. Initial VESS assessments were done at HAU a week before the  
168 first compaction treatments were applied in February 2012 and were repeated for all the  
169 replicate treatments at the end of each growing season either at the end of September or  
170 beginning of October 2012, 2013 and 2014.

### 171 2.3.3. Grass sward (perennial ryegrass) yield and quality

172 Grass yield data were collected from three cuts during the year, approximately early May,  
173 July and the end of August or early September (Table 1), from a strip (1.45m x10m) down  
174 the centre of the half of the plot (4m x 10m) reserved for yield measurements. These were  
175 taken using a Haldrup harvester (Haldrup Ltd, Germany). Grass yield was calculated from  
176 the fresh weight of the cut strip and a dry matter (DM) result taken from a grab sample of the  
177 fresh off-take from the plots. Analysis of the grass quality was done on separate sub  
178 samples of the fresh grass for crude protein (CP) (Kjeldahl digestion and analysis using the  
179 Gerhardt Vapodest system; calculated as  $\text{N} \times 6.25$ ), ash (MAFF/ADAS RB427), modified  
180 acid detergent (MAD) fibre (Clancy and Wilson, 1966), metabolisable energy (ME) and  
181 digestibility (D). The herbage N contents for each silage cut at the two sites were calculated  
182 from the N concentration and the DM yields (O'Connor et al, 2012):



183

#### 184 2.3.4 Weather data

185 Weather data were collected daily at 09:00hrs GMT at 1000m to the northeast of the  
186 experimental field at SRUC and 500m to the east of the experimental field at HAU (Table 2).

187

#### 188 2.3.5 Statistical analysis

189 Data were analysed using Genstat version 16 (VSN International, Hemel Hempstead). The  
190 trampled, tractor and no compaction treatments for bulk density, VESS, WFPS, DM yield,  
191 crop N content were analysed on a randomised basis using Genstat ANOVA on normally  
192 distributed data (tested with Shapiro-Wilks) within each year. Year was included as a factor  
193 for bulk density, VESS, WFPS, yield and N content and treatment x year significance  
194 assessed. Any significance was investigated with a post hoc Tukey's test at a level of  
195 significance of  $P < 0.05$ . Analysis was done separately for each experimental site. Linear  
196 regression analyses ( $P < 0.05$ ) were performed to determine relationships between the mean  
197 annual VESS and mean soil bulk density for the two experiments using Genstat V16 linear  
198 regression analysis.

199

### 200 **3. Results**

#### 201 3.1. Soil bulk density

202 At SRUC the compaction treatments increased mean soil bulk densities (0-10 cm) over the  
203 three years (Figure 1a) by 130 kg m<sup>-3</sup> for the trampled ( $P < 0.01$ ) and 210 kg m<sup>-3</sup> for tractor  
204 compaction ( $P < 0.001$ ) compared to the no compaction. Over the same period (October 2011  
205 to October 2014) the no compaction control treatment mean bulk densities showed an 80 kg  
206 m<sup>-3</sup> decrease at 0-10 cm and gave similar values for 10-20 cm.

207 There were differences in mean bulk densities between treatments at SRUC each year at 0-  
208 10 cm soil depth but only in October 2013 at 10-20 cm depth when the trampled treatment  
209 increased by 8.4% ( $P<0.01$ ) and the tractor increased by 9.4% ( $P<0.01$ ) compared to the no  
210 compaction (Figure 1b). In the final mean soil bulk density measurements (October 2014) at  
211 0 -10 cm, values had increased for the trampled by 18.2% ( $P<0.01$ ) and by 23.2% ( $P<0.01$ )  
212 for the tractor compaction, compared to the no compaction.

213 At HAU 0-10 cm depth, mean soil bulk densities did not change significantly over the three  
214 years of the experiment (Figure 1a), although values increased in the compaction treatments  
215 compared to a decrease in the no compaction treatment.

216

### 217 3.2. Water Filled Pore Space

218 At SRUC 0-10 cm soil depth, the annual mean WFPS values for no compaction were  
219 significantly lower than the corresponding trampled ( $P<0.01$ ) and tractor compacted soils  
220 ( $P<0.001$ ) during 2012 (Table 3). This trend continued through 2013, with a lower mean  
221 WFPS for the no compaction treatment ( $P<0.001$ ) compared with both compaction  
222 treatments. Again in 2014 the trampled ( $P<0.05$ ) and tractor ( $P<0.01$ ) compaction WFPS  
223 values were significantly higher than those for the no compaction treatment.

224 At 10-20 cm soil depth, at SRUC, the annual mean WFPS values showed a similar pattern to  
225 the 0-10 cm depth, with the compaction treatments having significantly greater WFPS values  
226 during 2012 and 2013 compared to the no compaction control. There was no significant  
227 compound affect of year on WFPS for either soil depth.

228

### 229 3.3. Visual Evaluation of Soil Structure (VESS)

230 At SRUC the mean VESS scores (Sq) (Figure 2) were generally greater (poorer soil  
231 structure) than at HAU and followed a similar pattern to the soil bulk density measurements,  
232 with tractor compaction showing a year on year increase after each subsequent compaction  
233 event. Over the three years the mean Sq increased by 0.81 ( $P<0.001$ ) for the trampled

234 treatment and increased by 1.44 ( $P<0.001$ ) for the tractor compaction, compared to the  
235 control.

236 At HAU, the mean Sq remained similar under the trampled compaction with only a 0.28  
237 increase, however, the tractor compaction increased by 1.02 ( $P<0.05$ ), after the second  
238 compaction event in February 2013.

239

#### 240 3.4. Silage dry matter yields

241 The SRUC trampling and tractor compaction treatments gave 8.4% and 10% reductions in  
242 overall mean DM yields (Figure 3), respectively, for all cuts over all three years compared to  
243 no compaction. At HAU, mean DM yields over the three years for all cuts were also  
244 decreased by 7.2% for trampling and by 4.8% for the tractor compaction, compared to the no  
245 compaction (Figure 3). There was a Year effect at SRUC ( $P<0.001$ ) with greater variability in  
246 yield year on year and 2014 provided significantly greater yields for trampled, tractor and no  
247 compaction compared to 2012 and 2013 but not at HAU where only the no compaction was  
248 significantly greater in 2014 ( $P<0.01$ ) and in the all years combined ( $P<0.05$ ).

249 At both sites the compaction treatments reduced the first silage DM yields the most,  
250 although not always significantly (Figure 4). The SRUC mean DM yield reductions for the  
251 trampling treatment, compared to the no compaction, were 16.3% ( $P<0.01$ ), 19.0% ( $P<0.05$ )  
252 and 10.3% ( $P<0.01$ ) for 2012, 2013 and 2014, respectively (Figure 4). The mean DM yield  
253 reductions for the tractor treatment were 15.0% ( $P<0.01$ ), 37.7% ( $P<0.001$ ) and 15.2%  
254 ( $P<0.01$ ) for 2012, 2013 and 2014, respectively. The first silage cut mean DM yields at HAU  
255 followed a similar pattern over the three years. These were reduced by 13.1% ( $P<0.001$ ),  
256 6.6% and 9.7% for 2012, 2013 and 2014, respectively for the HAU trampling compaction  
257 (Figure 4). The tractor compaction reduced mean DM yields, in the first cut, for 2012 and  
258 2014 by 7.4% and 14.9%, respectively, with no reduction for 2013.

259 At the second silage cut at SRUC, during 2012, the mean yields of the compaction  
260 treatments exceeded those of the no compaction treatment by 15.7% ( $P<0.01$ ) for trampling  
261 and 23.5% ( $P<0.001$ ) for tractor compaction, respectively, with smaller increases during

262 2013. Mean yields of the second cut silage increased at HAU during 2013 for the tractor  
263 compaction by 15.3% ( $P<0.05$ ). There was a year effect for the second silage cut at SRUC,  
264 especially for the compaction treatments ( $P<0.01$ ), whereas the no compaction produced  
265 similar yields during 2012 and 2013. The effect of year was less at HAU with trampled  
266 compaction being most significantly different ( $P<0.01$ ).

267 The compaction treatments reduced mean yields from the second cuts at both sites during  
268 2014 with 34.2% ( $P<0.05$ ) for the trampling and 35.6% ( $P<0.05$ ) for the tractor compaction at  
269 SRUC and 23.1% ( $P>0.05$ ) for the trampling and 16.9% ( $P>0.05$ ) for the tractor compaction  
270 at HAU.

271 During 2012 and 2013 the third cuts at SRUC gave smaller mean yield reductions as a result  
272 of compaction. However, the yields were similar for all the treatments during 2014. This  
273 pattern was not seen at HAU where the compaction continued to reduce mean DM yields  
274 by 10.0% for trampling and 19.3% for tractor compaction, although not significantly. Year on  
275 year changes were the least for the third cut yields at both sites, with only the compaction  
276 treatments providing a significant reduction during 2012 at SRUC.

277

### 278 3.5. Herbage N content

279 At SRUC the mean content of 1<sup>st</sup> cut herbage N over the three years was significantly  
280 greater in the trampled ( $P<0.05$ ) and tractor ( $P<0.01$ ) compaction treatments than for the no  
281 compaction (Figure 5). During 2012 the compaction treatments gave a significantly reduced  
282 mean herbage N content compared to the no compaction: tractor (107 g kg<sup>-1</sup> less ( $P<0.05$ ))  
283 and trampling (113 g kg<sup>-1</sup> less ( $P<0.05$ )).

284 However, no compaction at SRUC produced consistently greater mean herbage N contents  
285 than the compaction treatments for all the other silage cuts during the experiment, but these  
286 were only significant for the first silage cut for tractor compaction ( $P<0.05$ ) in 2013 and 2014.  
287 HAU mean herbage N contents for the three silage cuts over the three years were greater  
288 than those at SRUC with more significant differences between treatments (Figure 5). The no

289 compaction mean herbage N content was also significantly increased compared to the  
290 trampling treatment in the second ( $P<0.01$ ) and third ( $P<0.05$ ) silage cuts during 2014.  
291 A Year effect was seen for all three silage cuts at both SRUC ( $P<0.001$ ) and HAU ( $P<0.001$ ).  
292 These effects followed a similar pattern to the DM yield, especially with the increase at both  
293 sites for the 1<sup>st</sup> cut herbage N.

294

### 295 3.6. Regression analysis of VESS and bulk density

296 When the annual mean VESS scores for each experiment across the three years were  
297 compared with the annual mean soil bulk densities, there were significant linear regressions  
298 for both experiments (Figure 6). There was a stronger linear increase for SRUC  $R^2 = 0.97$   
299 ( $P<0.001$ ) than for HAU  $R^2 = 0.37$  ( $P<0.05$ ).

300

## 301 4. Discussion

302 The SRUC soil, with the greater clay content, showed the largest increase in mean soil bulk  
303 density after the first compaction treatments (November 2011). This accounted for 64% of  
304 the overall bulk density increase between October 2011 and October 2014, and agreed with  
305 other research (Taylor et al, 1982; Bakker and Davis, 1995) that showed up to 75% of soil  
306 compaction was the result of the first application of a repeated compaction treatment. It was  
307 surprising that the animal trampling increased soil compaction at 10 – 20 cm on the more  
308 clay soil, as it was assumed that this compaction would predominantly affect the upper 10  
309 cm due to the smaller area of application due to the heifers' foot area but similar pressures  
310 over a larger area for the tractor weight. Although, over the three years, the increase in soil  
311 bulk density was much less for the trampling (a 5.8% increase to  $1280 \text{ kg m}^{-3}$ ) than for the  
312 tractor compaction (a 9.7% increase to  $1340 \text{ kg m}^{-3}$ ;  $P<0.05$ ) at the 10-20 cm soil depth.

313 The increase in bulk density, at SRUC, for the tractor compaction at the 10-20cm soil depth  
314 was split between the first (40%) and second (47%) compaction events and indicated that  
315 repeated applications were needed to increase the density of the soil at this depth.

316 The reduction in bulk density, at both SRUC and HAU, over the three years for the no  
317 compaction control was (Figure 2) attributed to wetting and drying and freeze/thaw  
318 processes improving soil structure with soil contraction and expansion increasing porosity  
319 (Parker et al, 1982; Unger, 1991; Jabro et al, 2014). This reduction in soil bulk density was  
320 thus perhaps a result of the natural recovery of the soil from any compaction that had started  
321 before experimentation with careful reduction of any compaction treatment during the  
322 experiment.

323 The soil type at the HAU site contained a greater proportion of sand compared to the SRUC  
324 soil (over 18% at HAU compared to less than 14% at SRUC). Previous work has shown that  
325 sandy soils are more difficult to compact, as a result of the larger particle size (Bodman and  
326 Constantin, 1965; Keller and Håkansson, 2010). Nevertheless, there was still an increase in  
327 bulk density of 8% in the trampled treatment and of 6% for the tractor compaction at HAU,  
328 with a progressive decrease in structural quality over the three years of the experiment. Most  
329 of the bulk density increase at HAU occurred with the second and third compaction  
330 treatments, indicating the greater resistance to compaction of the sandier soil compared to  
331 the greater clay content soil at SRUC.

332 The mean WFPS values of ~ 100% for the compacted areas after high rainfall are an  
333 indication of the observed poor drainage due to the persistence of saturation, with pools of  
334 surface water ponding. The increased WFPS values down to 20 cm depth for both the  
335 trampled and tractor compaction indicated that the compaction was affecting porosity and  
336 hence the drainage down to this depth. The blocks of soil extracted for the VESS  
337 assessment of soil structure each October after compaction revealed obvious signs of poor  
338 drainage from the SRUC site with orange mottling coating root or worm channels, caused by  
339 oxidised iron deposits. Large, angular soil aggregates in the top 0-10 cm of the trampled soil  
340 and later to 20 cm in tractor compacted soil were visible and were symptomatic of poor soil  
341 quality. However, the no compaction treatment revealed a more friable, crumbly soil  
342 structure with small (approximately 2 cm diameter), rounded soil aggregates. Such soil  
343 structure would allow water to drain freely and would unlikely to be improved further by

344 management intervention. The reductions in mean DM yield were influenced by the  
345 decrease in soil structural quality from compaction (Bouwman and Arts, 2000) and the  
346 increased WFPS (Schulte et al., 2012).

347 The reductions in mean DM yield by compaction increased in general for both the  
348 experimental sites over the three years and by the third year the loss of DM yield was 11.4%  
349 for the trampling on the soil with the greater clay content and 12.0% on the sandier soil. The  
350 loss of mean DM yield from the tractor compaction was similar at both sites by the third year  
351 (14 - 15%). This indicated that soil type became less important as the accumulation of  
352 compaction increased. Balbuena et al. (2002) however, found larger grass yield reductions  
353 than those typically found in this study (40.3%) after one pass of a heavy (4200 kg) tractor  
354 on a fine clay loam soil, however, the tractor weight used was approximately 4 times greater  
355 than used in the current study.

356 The tractor compaction gave the greatest reduction in first cut mean DM yield in 2013 and  
357 2014 at SRUC but the trampled treatment gave the greater mean DM reduction for 2012.  
358 This latter reduction was unexpected as the greater compaction of the tractor was expected  
359 to reduce yield more, however, poaching was observed for the trampling compaction  
360 treatment as the soft surface soil was displaced up and around the heifers' feet as they  
361 moved across the pasture. Pande (2002) had found a reduction of 43% DM from a severe  
362 trampling event in the previous autumn due to damage of the grass tillers from trampling.

363 The increase in mean WFPS to > 70% by compaction, especially for extended periods of  
364 time, would have made the microbial population more anaerobic, with reduced efficiency in  
365 nutrient provision for the growing crop. This includes organisms that mineralise the applied  
366 organic fertiliser (Beylich et al., 2010).

367 The cooler weather in early 2013 (Table 2) most likely reduced yields at both SRUC and  
368 HAU (Figure 3), with the first cut DM yield being significantly reduced for SRUC (Figure 4).  
369 This indicated a compounding effect of soil compaction with weather conditions during early  
370 season growth.

371 Increases in the second silage cut mean DM yields in the compaction treatments at both  
372 SRUC and HAU, during the first two years of the experiments (2012 and 2013) were  
373 unexpected. These mid-season recoveries in yield could be explained by two factors. First,  
374 restriction in growth by compaction up to the first silage cut would result in lower soil nutrient  
375 use efficiency than by the no compaction sward and therefore more nutrients would have  
376 been available for growth up to the second cut for the compacted treatments. Second, the  
377 physical constraints of the compacted soil would be less effective as the growing season  
378 progressed and the soils became drier and warmer. This recovery of the second silage cut  
379 yield has been observed in a previous study by Douglas (1997) who attributed it to improved  
380 water retention in the compacted soil enabling better soil water supply in the drier parts of  
381 the growing season and to larger reserves of nutrients being available due to the reduction in  
382 leaching of these compared to a more porous less compacted soil.

383 Significant positive linear regressions between the number of days before  $\leq 2$ mm of rain fell  
384 after the first silage cut and the ratio of the compacted yield to no compaction yield for both  
385 the trampled ( $R^2=0.93$ ;  $P<0.03$ ) and tractor treatments ( $R^2=0.97$ ;  $P<0.01$ ) were seen for the  
386 more clay soil at SRUC. This increased yield from compacted soils for second cut silage was  
387 also found by Douglas (1997), who suggested the reduced soil porosity retained more water  
388 and reduced the loss of potential mineralisable nutrients from the top layer of the soil. These  
389 nutrients were then available for the grass roots and produced the increased yield compared  
390 to an uncompacted soil. However, there were negative regressions in the same parameters  
391 for the sandier, more well drained, soil at HAU, for both the trampled ( $R^2=0.97$ ;  $P<0.01$ ) and  
392 tractor compaction ( $R^2=0.96$ ;  $P<0.02$ ) indicating the soil water and nutrients drained away  
393 more easily; even with increased compaction. The sooner the rainfall after the first cut, the  
394 more likely these nutrients are to be leached. Nevertheless, by the third year of the  
395 experiment the effect of the soil compaction had now become apparent in the reduction in  
396 the second silage cut mean DM yields, especially at SRUC. This indicated that the  
397 accumulated compaction damage to the soil structure from 2011/2012 to 2014 appeared to



398 have produced a progressive effect on reducing DM yield and the advantage of compaction  
399 retaining soil water and nutrients for the second silage cut had been lost.

400 The increased mean herbage N content at HAU compared to SRUC was an effect of both a  
401 greater off-take of herbage and higher crude protein content, as a consequence of the soil  
402 with the greater sand content at HAU provided overall better growing conditions.

403 The lower uptake of N in the herbage of the compaction treatments for the majority of the  
404 silage cuts at both sites was expected as the N content was linked to overall off-take and  
405 there was less herbage on the compacted treatments. A greater mean N content in the  
406 herbage did indicate a greater mean N content in the herbage may be the consequence of a  
407 greater efficiency in N usage and uptake from the soil, especially under the no compaction.

408 As the same amount of N was applied to all three treatments, reduced uptake of N in the  
409 compaction treatments indicated that more N remained in the soil after cutting, with the  
410 potential for diffuse pollution through run off and leaching (Di and Cameron, 2002).

411 Increased soil bulk density and a change in a visual soil evaluation score, indicative of  
412 poorer structure, have been shown to be positively correlated in previous work (Newell-Price  
413 et al., 2013; Mueller et al., 2013). This was also the case in both the current experiments for  
414 the mean VESS score for the top 10cm and the mean soil bulk density, over the three years  
415 (Figure 6). However, the linear regression for the top 10 cm in the more clay soil at SRUC  
416 was much stronger ( $R^2=0.97$  ( $P<0.001$ )) than the sandier soil at HAU ( $R^2=0.37$  ( $P<0.05$ ))  
417 and would indicate levels of compaction that corresponds more closely with bulk density.

418 This would allow VESS to be used to indicate levels of compaction, however, the  
419 relationships would be dependant on the type of soil.

420 Newell-Price et al (2013) surveyed soil structural conditions in English and Welsh grasslands  
421 and found strong correlations between the scores of the two visual assessment methods  
422 used, the visual soil assessment (vsa) method from New Zealand (Shepherd, 2009); the  
423 Peerlkamp (soil structure – ‘St’) method (Peerlkamp, 1967) and the bulk density in the top 10  
424 cm of the soil. Both of these visual assessment methods have similar criteria to VESS.

425 Newell-Price et al (2013) estimated that approximately 8 to 12% of the grassland soils

426 surveyed were in a poor condition and would have resulted in an obvious reduction in  
427 grassland yield. A further 54 to 63% of the grassland swards surveyed had soil in a  
428 moderate condition that was deemed likely to have reduced yield. The bulk density values  
429 and VESS scores of the compaction treatments in these experiments, especially after three  
430 years of compaction treatments would correspond to the moderate conditions of Newell-  
431 Price et al (2013). The estimation that about 2 to 3 million ha of grassland in England and  
432 Wales were only in a moderate condition would equate to a loss in DM yield of between 5.6  
433 and 8.4 Mt from trampling and 6.0 and 9.0 Mt from tractor traffic depending on the soil type,  
434 based on the losses seen from the experiments described here.

435

## 436 5. Conclusions

437 Damage to soil structure through compaction reduced the yields of grassland swards that  
438 were affected by both animal trampling (between 11.4 and 12.0%) and by mechanical  
439 (tractor) compaction (14.5% reduction) after three years of these treatments. Soil WFPS was  
440 increased by the compaction treatments with soils being less free draining. The soil type  
441 contributed towards yield losses with a finer textured soil with a greater clay content showing  
442 a greater loss from tractor compaction during cold wet weather than a more easily drained  
443 sandier soil. Both soil types showed the greatest DM yield reductions for the first silage cut  
444 especially when there had been colder, wetter weather during the initial growing period.

445 As the herbage N content of the swards decreased with increased compaction there was the  
446 potential for increased N loss through the soil and less efficient use by the crop. Close linear  
447 regressions were seen between the soil visual assessment method and the physical  
448 measurements of soil bulk density indicating the potential for the VESS method to be used  
449 as a management tool to assess the level of compaction in grassland and indicate the  
450 correct management to rectify soil structure and thereby increase DM yield.

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619 **Table 1. Timings of compaction treatments, grass silage cuts and fertiliser applications**  
 620 **for SRUC, Dumfries and HAU, Newport (numbers in brackets refer to the silage cut).**

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Treatment	Experimental Site	
	SRUC	HAU
Compaction	November 2011	February 2012
	November 2012	February 2013
	November 2013	February 2014
Urea application	Late March 2012	Early April 2012
	Mid March 2013	Early April 2013
	Late March 2014	Mid March 2014
Slurry application	Late May 2012	Late June 2012
	Mid July 2012	Late August 2012
	Mid June 2013	Late May 2013
	Late July 2013	Mid July 2013
	Mid June 2014	Mid May 2014
	Mid April 2014	Late June 2014
Silage cutting	Mid May 2012 (1)	Late May 2012 (1)
	Late June 2012 (2)	Late July 2012 (2)
	Early September 2012 (3)	Late September 2012 (3)
	Late May 2013 (1)	Late May 2013 (1)
	Mid July 2013 (2)	Early July 2013 (2)
	Early September 2013 (3)	Late August 2013 (3)
	Early June 2014 (1)	Mid May 2014 (1)
	Mid July 2014 (2)	Late June 2014 (2)
	Early September 2014 (3)	Mid August 2014 (3)

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630 **Table 2. Mean annual air temperature (°C) and mean and yearly total rainfall (mm) for**  
 631 **SRUC and HAU for the three years of the experiment and mean temperatures (°C) and**  
 632 **rainfall (mm) split into growing periods for the grass silage.**

Year		Month				Annual mean
SRUC	Jan-April	May-July	Aug-Sep	Oct-Dec		
Air Temp mean (°C)	<b>2012</b>	6.5	12.8	14.0	6.3	9.9
	<b>2013</b>	4.4	14.2	14.3	8.1	10.3
	<b>2014</b>	7.0	14.6	14.7	8.1	11.1
	<b>Long-term mean*</b>	<b>5.7</b>	<b>13.3</b>	<b>14.1</b>	<b>6.9</b>	<b>10.0</b>
<b>HAU</b>						
Air Temp mean (°C)	<b>2012</b>	6.3	13.9	14.7	6.8	10.4
	<b>2013</b>	4.3	13.7	14.8	8.4	11.3
	<b>2014</b>	7.6	15.3	14.9	8.3	11.5
	<b>Long-term mean*</b>	<b>7.7</b>	<b>17.0</b>	<b>14.7</b>	<b>6.9</b>	<b>11.6</b>
<b>SRUC</b>						
		Jan-April	May-July	Aug-Sep	Oct-Dec	Annual total
Rainfall total (mm)	<b>2012</b>	227.8	368.4	275.4	486.6	1358.2
	<b>2013</b>	285.9	256.6	138.2	471.2	1151.9
	<b>2014</b>	428.8	176.3	119.9	536.9	1261.9
	<b>Long-term mean*</b>	<b>347.1</b>	<b>213.9</b>	<b>183.8</b>	<b>376.1</b>	<b>1120.9</b>
<b>HAU</b>						
Rainfall total (mm)	<b>2012</b>	275.2	298.1	188.5	256.3	1018.1
	<b>2013</b>	190.4	198.6	158.1	193.2	740.3
	<b>2014</b>	276.4	181.7	100.2	217.8	776.1
	<b>Long-term mean*</b>	<b>190.9</b>	<b>160.8</b>	<b>116.6</b>	<b>191.6</b>	<b>659.9</b>

633 \*Long-term mean 1981-2010

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635 **Table 3. Mean annual water filled pore space (%) values for the no compaction and**  
 636 **compaction treatments (Trampled and Tractor compaction) for 2012, 2013 and 2014 at**  
 637 **SRUC (values in brackets s.e.d. for compaction treatment compared to no**  
 638 **compaction).**

	No Compaction	Trampled	Tractor	P value	No of reps
<b>0-10cm</b>					
2012	71.1	82.8 (3.12)	88.7 (3.53)	<0.001	9
2013	74.7	90.1 (3.49)	93.4 (3.77)	<0.001	3
2014	67.8	86.4 (8.57)	91.2 (8.18)	0.01	3
<b>10-20cm</b>					
2012	74.6	81.3 (8.18)	86.4 (2.47)	<0.001	9
2013	75.0	84.2 (2.71)	86.7 (2.80)	<0.001	3
2014	69.5	79.2 (6.09)	83.3 (7.19)	0.07	3

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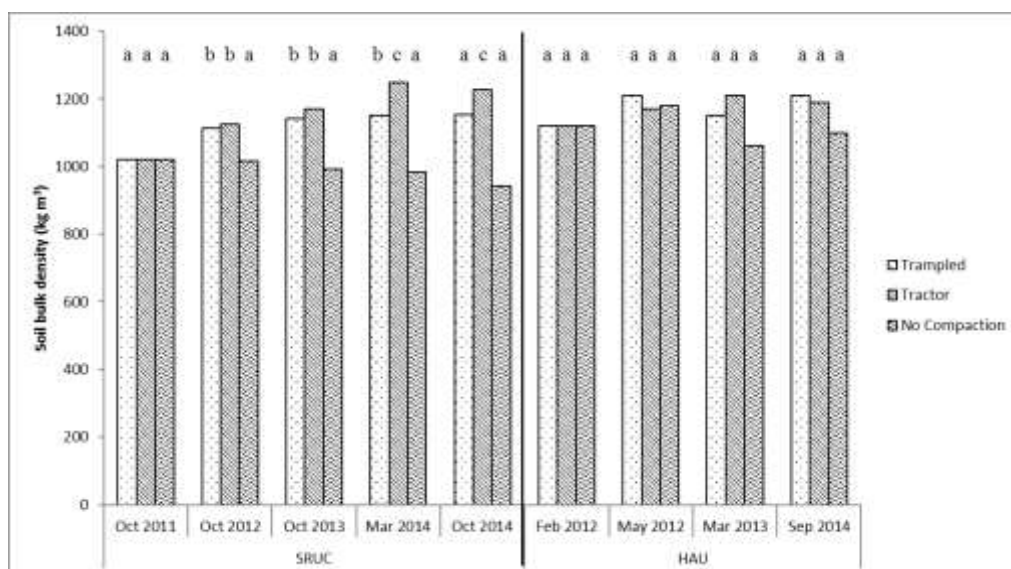
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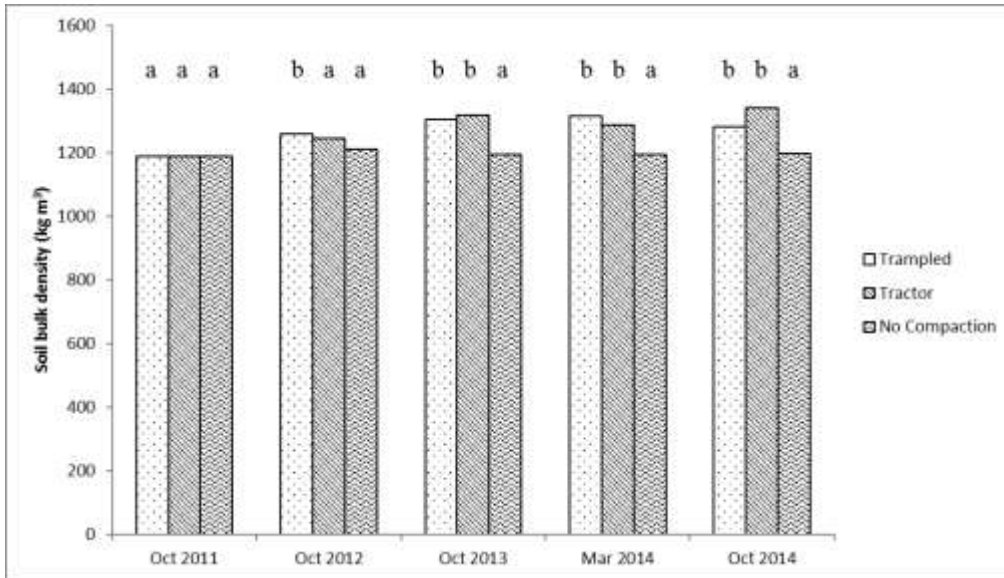
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649 a) SRUC and HAU (0-10cm soil depth)



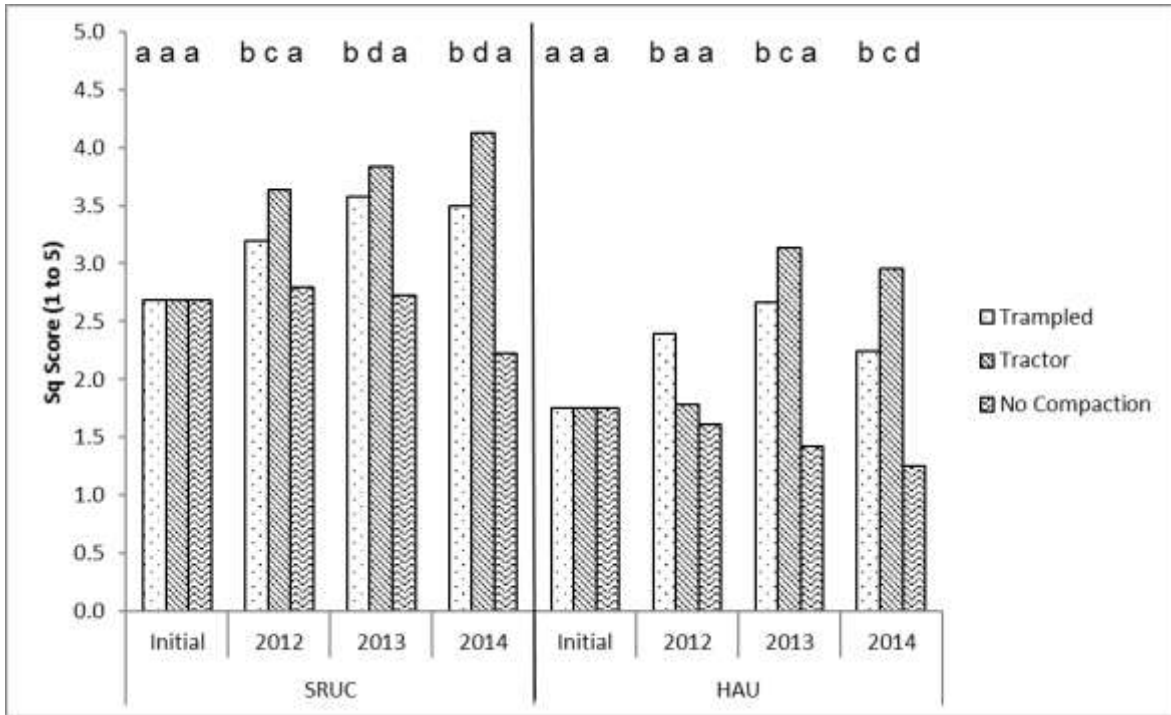
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651 **b) SRUC (10-20cm soil depth)**

652 **Figure 1. Mean bulk densities (g cm<sup>-3</sup>) for the no compaction, trampled and tractor**  
 653 **compaction treatments at a) SRUC and HAU at 0 – 10 cm depth and b) SRUC at 10 –**  
 654 **20 cm, between 2011 and 2014. Letters indicate significant differences (P < 0.05)**  
 655 **between means (each site analysed separately).**

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659 **Figure 2. Mean Visual Evaluation of Soil Structure (VESS) scores (Sq Score 1 to 5)**  
 660 **from initial pre-treatment soils and post-compaction treatment soils (trampled, tractor**  
 661 **and no compaction) for SRUC and HAU. Letters indicate significant differences (P <**  
 662 **0.05) between means (each site analysed separately).**

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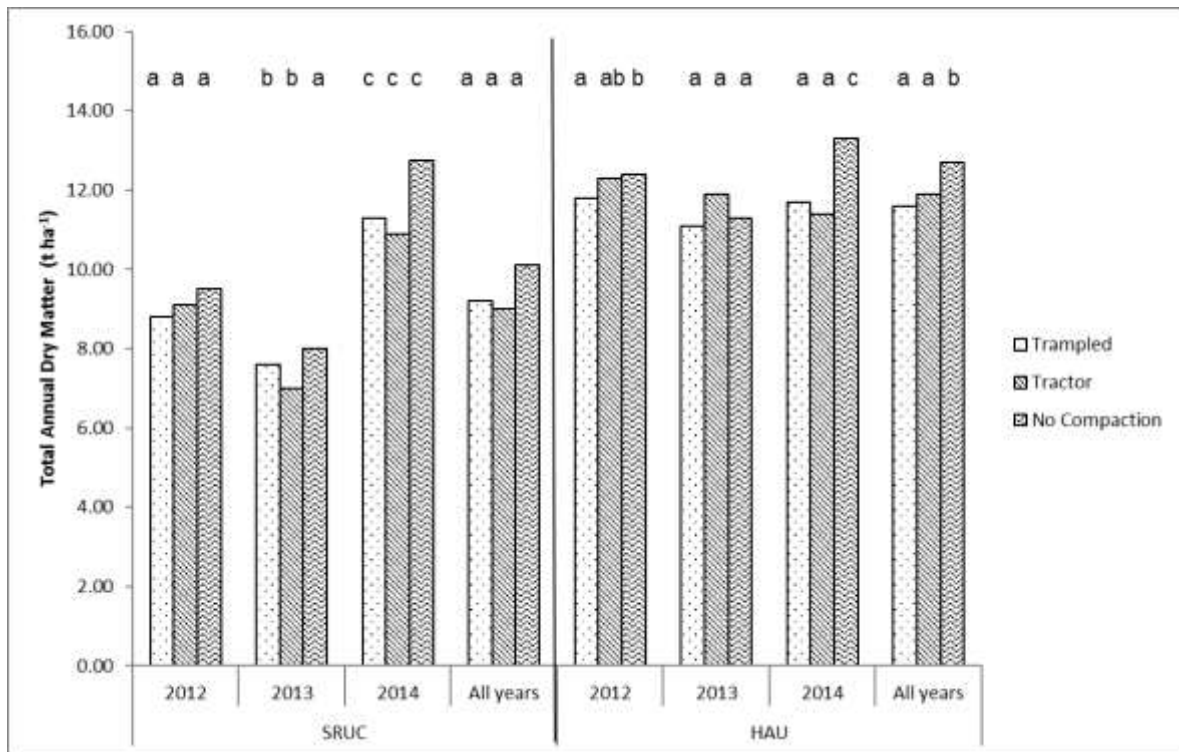
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673 **Figure 3. Annual and all-year means of combined silage dry matter yields (t ha<sup>-1</sup>) from**  
 674 **the no compaction, trampled and tractor compaction treatments from SRUC and HAU**  
 675 **for the years 2012 to 2014. Letters indicate significant differences (P < 0.05) between**  
 676 **means (each site analysed separately).**

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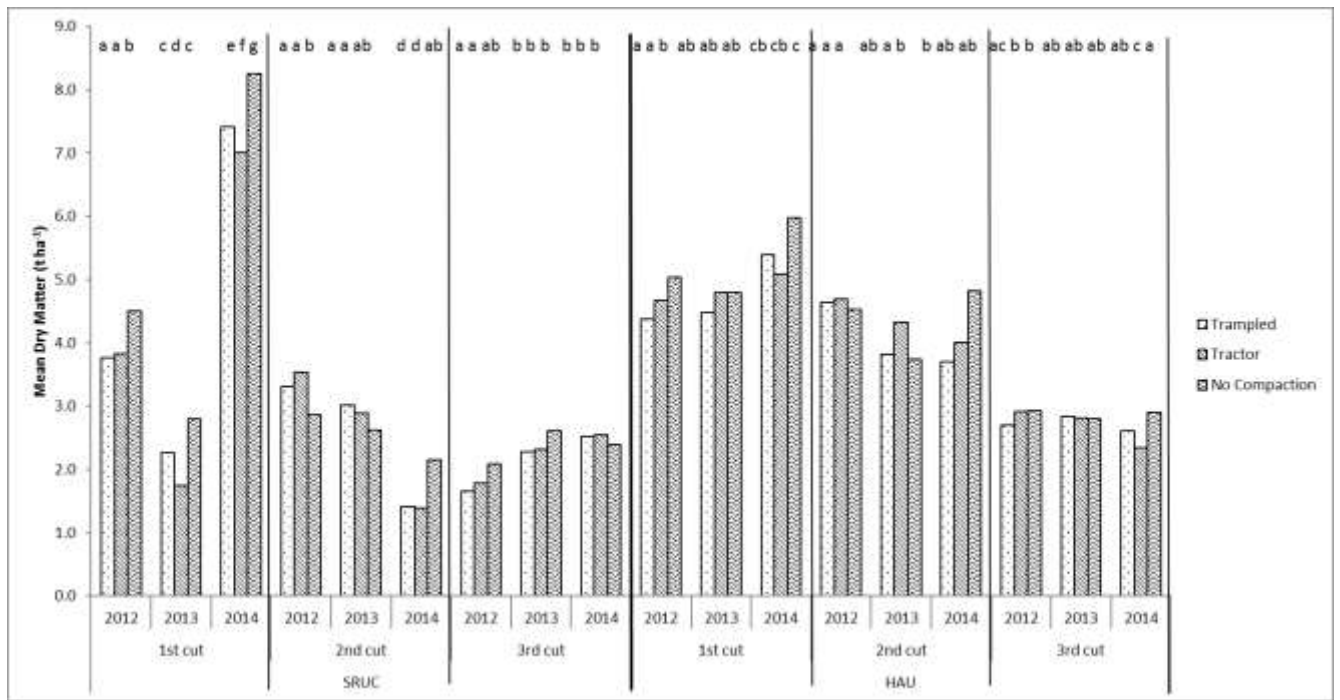
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686 **Figure 4. Mean silage dry matter yields (t ha<sup>-1</sup>) for individual cuts from the no**  
 687 **compaction, trampled and tractor compaction treatments from SRUC and HAU for**  
 688 **2012, 2013 and 2014. Letters indicate significant differences (P < 0.05) between means**  
 689 **within each silage (each site analysed separately).**

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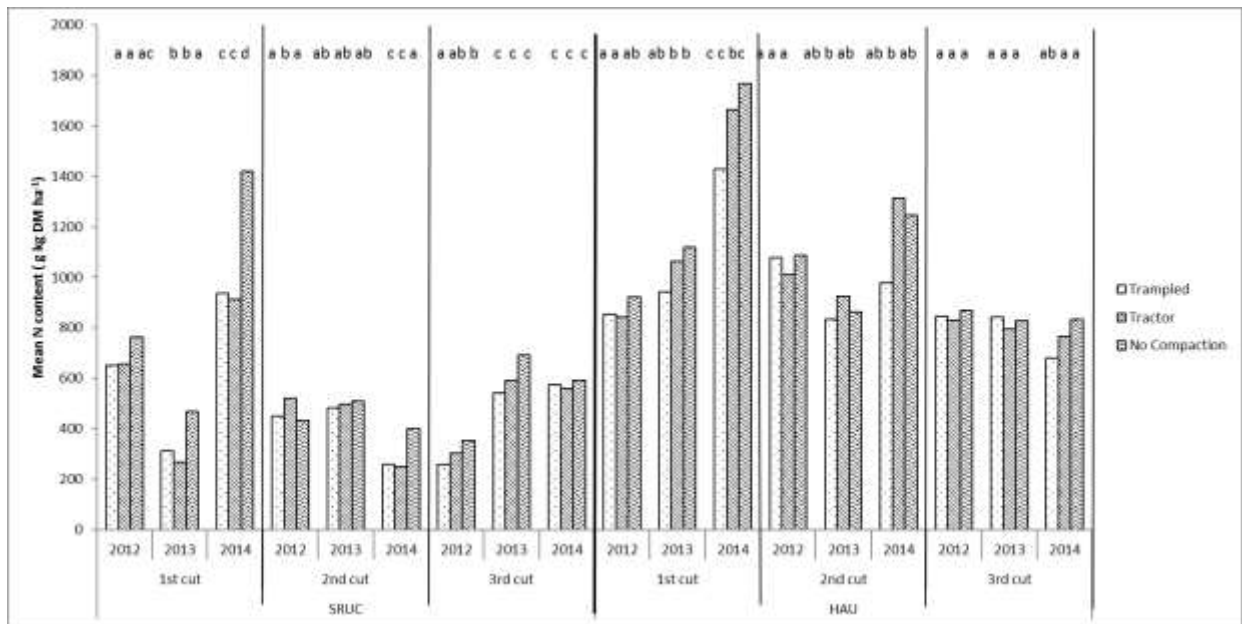
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698 **Figure 5. Mean herbage N content (g kg DM ha<sup>-1</sup>) from the no compaction, trampling**  
 699 **and tractor compaction areas for individual and total cuts from SRUC and HAU for the**  
 700 **years 2012 to 2014. Letters indicate significant differences (P < 0.05) between means**  
 701 **of each silage cut within each year (each site analysed separately).**

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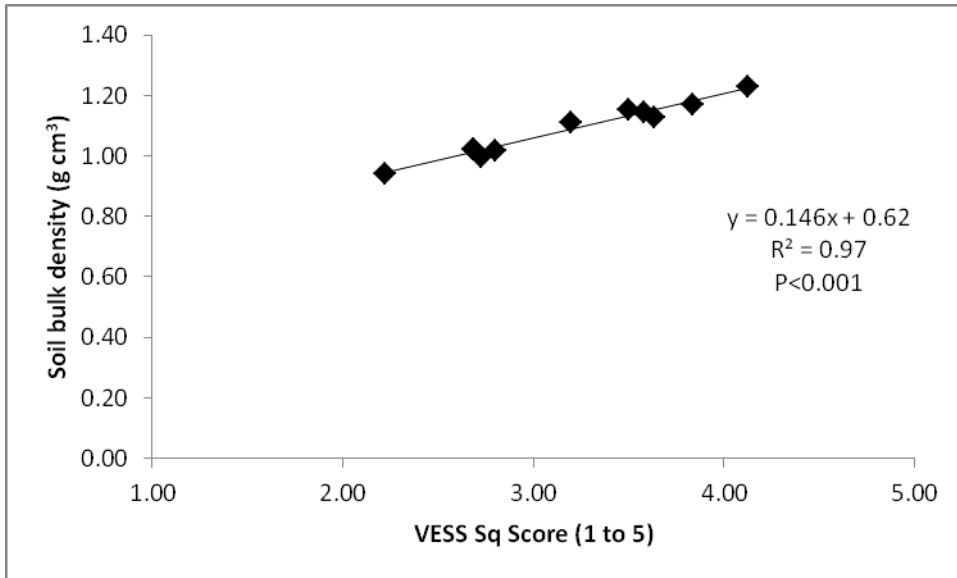
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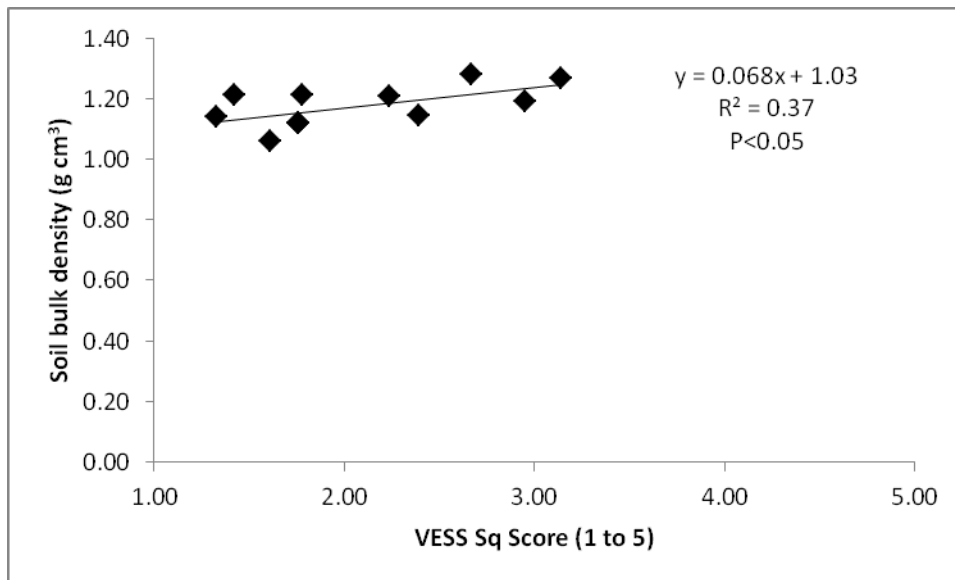
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712 a) SRUC



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714 b) HAU

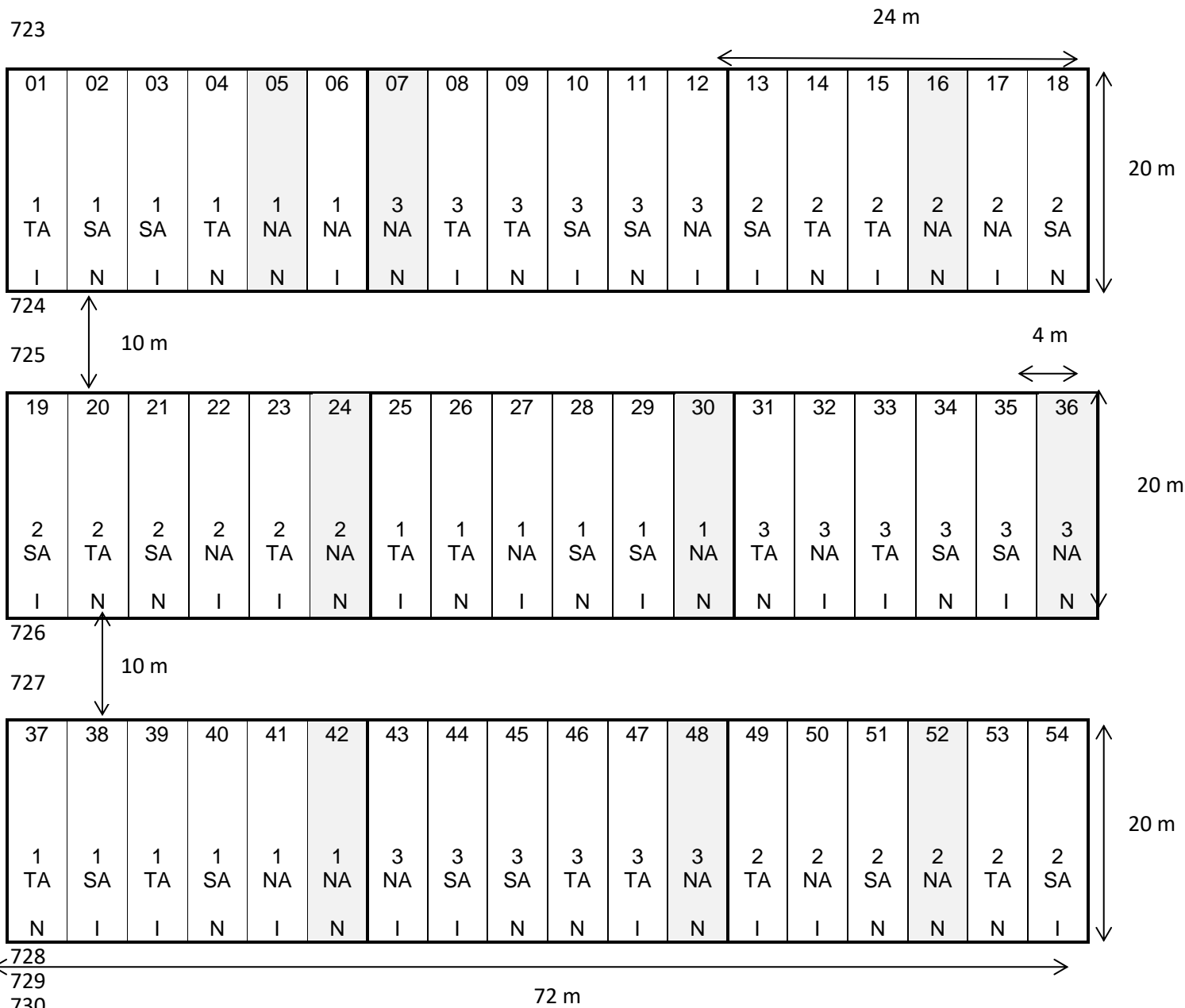
715 **Figure 6. Regression between the annual mean soil VESS scores (1 (best structure) to**  
 716 **5 (poorest structure)) and the annual mean soil bulk density (g cm<sup>-3</sup>) at 0 to 10cm**  
 717 **depth for all the three treatments (trampling, tractor and no compaction) for 2012,**  
 718 **2013 and 2014, including initial bulk density before the start of the experiment (2011)**  
 719 **at a) SRUC – a more clay soil and b) HAU – a sandier soil.**

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- 732 1 = Trampling compaction,
- 733 2 = No Compaction
- 734 3 = Tractor compaction
- 735 TA = Surface aeration, SA = Sward lifter aeration, NA = No aeration
- 736 N = No Nitrification inhibitor, I = Nitrification inhibitor

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738 The data used in this study were from the no nitrification inhibitor and no aeration in sub-

739 treatments in each of the replicate blocks.

740 **Supplementary Figure 1. Layout of main treatments and sub-treatments areas of the**

741 **whole compaction experiment.**

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