

Scotland's Rural College

## **Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands**

Abdalla, M; Hastings, A; Chadwick, DR; Jones, DL; Evans, CD; Jones, MB; Rees, RM; Smith, P

*Published in:*  
Agriculture, Ecosystems and Environment

*DOI:*  
[10.1016/j.agee.2017.10.023](https://doi.org/10.1016/j.agee.2017.10.023)

First published: 06/11/2017

*Document Version*  
Publisher's PDF, also known as Version of record

[Link to publication](#)

### *Citation for published version (APA):*

Abdalla, M., Hastings, A., Chadwick, DR., Jones, DL., Evans, CD., Jones, MB., Rees, RM., & Smith, P. (2017). Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. *Agriculture, Ecosystems and Environment*, 253, 62 - 81. <https://doi.org/10.1016/j.agee.2017.10.023>

### **General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

### **Take down policy**

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

1 **Critical review of the impacts of grazing intensity on soil organic carbon storage and**  
2 **other soil quality indicators in extensively managed grasslands**  
3

4 M. Abdalla<sup>a</sup>, A. Hastings<sup>a</sup>, D.R. Chadwick<sup>b</sup>, D.L. Jones<sup>b</sup>, C.D. Evans<sup>b</sup>, M.B. Jones<sup>c</sup>, R.M.  
5 Rees<sup>d</sup>, P. Smith<sup>a</sup>  
6

7 <sup>a</sup>*Institute of Biological and Environmental Sciences, School of Biological Sciences,*  
8 *University of Aberdeen, Aberdeen, AB24 3UU, UK*

9 <sup>b</sup>*School of the Environment, Natural Resources and Geography, Bangor University, Bangor,*  
10 *Gwynedd, LL57 2UW, UK*

11 <sup>c</sup>*Department of Botany, School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland*

12 <sup>d</sup>*Scotland's Rural College (SRUC) Edinburgh, West Mains Road, Edinburgh EH93JG, UK*  
13

14 **Keywords:** Grazing; Soil organic carbon; Grassland; Grazing intensity; Total nitrogen  
15  
16  
17  
18  
19  
20  
21  
22

23 Corresponding author:

24 Dr. Mohamed Abdalla  
25

26 Address: Institute of Biological and Environmental Sciences, School of Biological  
27 Sciences, University of Aberdeen, 23 St. Machar Drive, Aberdeen, AB24 3UU, UK

28 Email address: mabdalla@abdn.ac.uk

29 Phone no.: Mobile: 00447468316456

30 Fax no.: 00441224 272703  
31  
32  
33  
34

35 **Critical review of the impacts of grazing intensity on soil organic carbon storage and**  
36 **other soil quality indicators in extensively managed grasslands**

37  
38 M. Abdalla<sup>a</sup>, A. Hastings<sup>a</sup>, D.R. Chadwick<sup>b</sup>, D.L. Jones<sup>b</sup>, C.D. Evans<sup>b</sup>, M.B. Jones<sup>c</sup>, R.M.  
39 Rees<sup>d</sup>, P. Smith<sup>a</sup>

40  
41 <sup>a</sup>*Institute of Biological and Environmental Sciences, School of Biological Sciences,*  
42 *University of Aberdeen, Aberdeen, AB24 3UU, UK*

43 <sup>b</sup>*School of the Environment, Natural Resources and Geography, Bangor University, Bangor,*  
44 *Gwynedd, LL57 2UW, UK*

45 <sup>c</sup>*Department of Botany, School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland*

46 <sup>d</sup>*Scotland's Rural College (SRUC) Edinburgh, West Mains Road, Edinburgh EH93JG, UK*

47

48 **Keywords:** Grazing; Soil organic carbon; Grassland; Grazing intensity; Total nitrogen

49

50 **Abstract**

51

52 Livestock grazing intensity (GI) is thought to have a major impact on soil organic carbon  
53 (SOC) storage and soil quality indicators in grassland agroecosystems. To critically  
54 investigate this, we conducted a global review and meta-analysis of 83 studies of extensive  
55 grazing, covering 164 sites across different countries and climate zones. Unlike previous  
56 published reviews we have normalized the SOC and total nitrogen (TN) data to a 30 cm depth  
57 to be compatible with IPCC guidelines. We also calculated a normalized GI and divided the  
58 data into four main groups depending on the regional climate (dry warm, DW; dry cool, DC;  
59 moist warm, MW; moist cool, MC). Our results show that taken across all climatic zones and  
60 GIs, grazing results in a decrease in SOC storage, although its impact on SOC is climate-  
61 dependent. All GI levels increased SOC stocks under the MW climate (+7.6%) whilst there  
62 were reductions under the MC climate (-19%). Nevertheless, under the DW and DC climates,  
63 only the low (+5.8%) and low to medium (+16.1%) grazing intensities, respectively, were  
64 associated with increased SOC stocks. High GI significantly increased SOC for C4-  
65 dominated grassland compared to C3-dominated grassland and C3-C4 mixed grasslands. It  
66 was also associated with significant increases in rate of TN change and bulk density but has  
67 no effect on soil pH. To protect grassland soils from degradation, recommended GI and  
68 management practices will differ according to climate region and grass's type (C3 or C4 or  
69 C3-C4 mixed).

70

71 **1. Introduction**

72

73 Grasslands cover approximately 40% of the earth's land surface (Wang and Fang, 2009) and  
74 represent about 70% of the agricultural area (Conant, 2012). They store about 10% of  
75 terrestrial biomass and make a contribution of about 20-30% to the global pool of soil organic  
76 carbon (SOC) (Scurlock and Hall, 1998; Conant et al., 2012). Grasslands have some potential  
77 to sequester atmospheric CO<sub>2</sub> as stable carbon (C) in the soil (Reid et al., 2004) and hence  
78 could contribute to mitigation of climate change (Allard et al., 2007). However, the  
79 accumulation and storage of C in grasslands is influenced by many factors especially biotic  
80 factors e.g. grazing intensity (GI), animal type and grass species (Conant et al., 2001; Olff et  
81 al., 2002; Jones and Donnelly, 2004; McSherry and Ritchie, 2013). Nevertheless, although  
82 grasslands have high SOC contents, recent studies have suggested that intensive livestock  
83 management has led to C losses from many grasslands around the world and thereby,  
84 grassland soils could become a source rather than a sink for greenhouse gas (GHG) emissions  
85 (Janzen, 2006; Ciais et al., 2010; Powlson et al., 2011). Grazing intensity has the potential to  
86 modify soil structure, function and capacity to store organic carbon (OC) (Cui et al., 2005)  
87 and could significantly change grassland's C stocks (Cui et al., 2005). As SOC has a major  
88 influence on soil physical structure and a range of ecosystem services (e.g. nutrient retention,  
89 water storage, pollutant attenuation), its reduction could lead to reduced soil fertility and  
90 consequently, land degradation (Rounsevell et al., 1999) and a high risk under climate change  
91 (Lal, 2009). However, investigating the effects of GI on SOC is hampered by the  
92 heterogeneity in grassland types and variations in environment. This is exacerbated by the  
93 fact that all previous published meta-analyses studies on this topic (e.g. McSherry and  
94 Ritchie, 2013; Lu et al., 2017; Zhou et al., 2017) pooled the data of different studies together  
95 without considering the differences in soil depth at which the SOC, and TN were measured  
96 thus producing highly uncertain/contradictory results.

97

98 High GI and moisture gradients (Cingolani et al., 2005) could indirectly alter grass  
99 species composition by decreasing water availability (Pineiro et al., 2010). This decreases  
100 plant community composition, aboveground biomass, leaf area and light interception and  
101 thereby, net primary production (NPP) (Manley et al., 1997; Hart, 2001; Pineiro et al., 2010).  
102 However, according to Derner and Schuman (2007), Pineiro et al. (2010) and McSherry and  
103 Ritchie (2013), high GI can increase soil C sequestration but only when mean annual

104 precipitation is 600 mm or less with different responses received from different soil types. It  
105 has also been shown to increase root C contents (a primary control of SOC formation) at the  
106 driest and wettest sites, but decrease root C contents at intermediate precipitation levels (400  
107 mm to 850 mm) (Pineiro et al., 2010). Wang et al. (2017) reported that the composition of  
108 plant species and soil condition in the Tibetan pastures were not only affected by GI but also  
109 by the local environmental factors. Moreover, Russell et al. (2013) found that a short period  
110 of mob grazing (grazing at high intensity for a short period of time) was effective at  
111 increasing soil organic matter and diversity in forage species composition. Though,  
112 overgrazing to the point of stripping surface vegetation can result in soil-degradation and loss  
113 of the fertile topsoil, especially where precipitation is low and evaporation is high (Xie and  
114 Wittig, 2004).

115

116 Furthermore, high GI can alter SOC by changing the competitive abilities of different  
117 microbial phyla because of the link between GI, carbon availability and ecosystem functions  
118 (Eldridge et al., 2017a). However, the relationship between GI and SOC is non-linear  
119 (Eldridge et al., 2017b). Previous studies have found mixed results (Derner et al., 2006;  
120 McSherry and Ritchie, 2013; Zhou et al., 2017), with studies showing increases (Reeder and  
121 Schuman, 2002; Li et al., 2011; Silveira et al., 2014), no affect (Frank et al., 2002; Shrestha  
122 and Stahl, 2008; Cao et al., 2013) or decreases (Zuo et al., 2008; Golluscio et al., 2009;  
123 Reszkowska et al., 2011; Qiu et al., 2013) in SOC stocks. The review by McSherry and  
124 Ritchie (2013) showed that GI effects on SOC are highly context-specific, where higher GI  
125 increased SOC on C4-dominated and C4-C3 mixed grasslands, but decreased SOC in C3-  
126 dominated grasslands. Other recent reviews by Lu et al. (2017) and Zhou et al. (2017) found  
127 that high GI significantly decreased belowground C and N pools. They found GI interacts  
128 with elevation and mean annual temperature (Lu et al., 2017), or with soil depth, livestock  
129 type and climatic conditions (Zhou et al., 2017).

130

131 Understanding the impacts of GI on SOC accumulation and storage in grasslands is  
132 crucial to provide the most effective soil C management options. However, although all those  
133 previous reviews are valuable, scientific understanding would be improved by normalizing  
134 the sampling depth and GI. In this study, to be compatible with the IPCC guidelines, reduce  
135 these errors and make a comprehensive evaluation for GI we have normalized the soil depth  
136 for all studies to 30 cm using a quadratic density function based on Smith et al. (2000) and  
137 calculated a normalized GI. The major objective of this meta-analysis was to investigate the

138 impacts of GI on SOC in extensively grazed grassland soils at a global scale. Additionally,  
139 and because of its importance for C biogeochemistry, we discuss the impacts of GI on total  
140 nitrogen (TN) and other soil properties (mainly pH and bulk density) in grasslands. We also  
141 investigated whether climatic variations can control the ecological effects of GI practices on  
142 SOC in grasslands. The specific hypotheses we critically evaluated are as follows: 1) higher  
143 GI decreases SOC and TN in soils 2) the impacts of GI on SOC are modified by  
144 environmental and biotic factors, and 3) the effects of GI on SOC stocks depends on climatic  
145 zone and soil texture.

146

## 147 **2. Materials and Methods**

148

### 149 *2.1. Data collection*

150 To collect published studies that have investigated the impacts of GI on SOC and other  
151 selected soil properties (TN, pH and BD ) under grassland, we performed a comprehensive  
152 search on the Web of Science database (accessed between January 2015 and February 2017)  
153 using the keywords: grazing; soil organic carbon; grassland; GI; total nitrogen and carbon  
154 sequestration. In an attempt to have the best possible coverage, we also checked all references  
155 in the papers found in the Web of Science search. Only studies which were longer than one  
156 year and measured SOC or TN were selected. This study accounted for the differences in  
157 grass growing seasons at each experimental site. Our searches resulted in 83 studies that  
158 investigated the impacts of grazing on SOC and other selected soil properties, carried out at  
159 164 sites covering different countries, climatic zones and management systems (Fig. 1). The  
160 studies were segregated into four groups depending on the regional climate zones (dry cool  
161 (DC); dry warm (DW); moist cool (MC) and moist warm (MW)).

162

163 We defined the climatic zones based on thermal and moisture regimes: cool, warm,  
164 dry, and moist zone according to Smith et al. (2008). The cool zone covers the temperate  
165 (oceanic, sub-continental, and continental) and boreal (oceanic, sub-continental and  
166 continental) areas, whilst the warm zone covers the tropics (lowland and highland) and  
167 subtropics (summer rainfall, winter rainfall, and low rainfall) areas. The dry zone includes the  
168 areas where the annual precipitation is equal or below 500 mm, whilst the moist zone  
169 includes areas where the annual precipitation is above 500 mm. Coordinates, grass type (i.e.  
170 shrubby, woody, steppe, and prairie), annual mean climatic conditions as well as grazing  
171 details, soil texture, original depth (OD), initial and final BD and pH, changes in SOC and

172 TN ( $\text{kg m}^{-2}$ ); values were added where available or we put plus (+) for increased and minus (-  
173 ) for decreased, as shown in Tables 1-4.

174

## 175 2.2. Estimation methods applied

176 In some studies SOC and TN values are given as concentrations. To convert these values to  
177 stocks ( $\text{kg m}^{-2}$ ), the following equations were applied (IGBP-DIS, 1998):

178

$$179 \text{SOC (kg m}^{-2}\text{)} = [\text{depth (cm)} * \text{BD (g cm}^{-3}\text{)} * \text{SOC (\%C in g per100g soil)}]/1000 \quad (1)$$

180

$$181 \text{TN (kg m}^{-2}\text{)} = [\text{depth (cm)} * \text{BD (g cm}^{-3}\text{)} * \text{TN (\%TN in g per100g soil)}]/1000 \quad (2)$$

182

183 In cases where there were more than one year of values reported in the original paper we used  
184 the mean value in this meta-analysis. However, because studies reported the SOC and TN  
185 content from different soil depths, we used a quadratic density function based on Smith et al.  
186 (2000) to derive a scaling cumulative distribution function (c.d.f.) for soil density as a  
187 function of soil depth up to 1m. This allows SOC and TN at a given depth  $d$  (m) to be scaled  
188 to the equivalent values at 0.30 m as follows:

189

$$\text{cdf}(d) = \left( 22.1 - \frac{33.3d^2}{2} + \frac{14.9d^3}{3} \right) / 10.41667 \quad (3)$$

190

$$191 \text{SOC}(0.3\text{m}) = \text{SOC}(d) \times (\text{cdf}(0.3)) / (\text{cdf}(d)) \quad (4)$$

192

193 Different methods were used to measure soil pH in different studies, e.g. using pH  
194 probe/meter in deionized water or 0.01 M  $\text{CaCl}_2$  in 1:1 and 1:2 or 1:5 (v:v) soils: solution  
195 ratios. We did not adjust pH results recorded by different methods, but where a range of  
196 values were reported, we took the mean value. Also, where a range of air temperatures was  
197 reported, we used mean annual value in degree Celsius ( $^{\circ}\text{C}$ ) as reported for the years of the  
198 study in the meta-analysis. The mean annual precipitation (mm) value for each study period  
199 was taken from the original papers. However, where the mean annual precipitation or mean  
200 annual temperature were not reported, those values were taken from the CRU 3.24 climate  
201 data set (Harris et al., 2013).

202

203 The GI reported in each of the studies was estimated in different ways, and was  
 204 usually subjective considering local practices, usually described as high, medium (or  
 205 moderate) and low. To undertake this analysis we required a continuous variable for grazing  
 206 intensity and so the method described below was developed for this study and used to classify  
 207 the GI used for each of the experiments in a comparable way. As available fodder was not  
 208 described in all studies it was necessary to estimate the amount of plant dry material available  
 209 (DM) on each site annually and to calculate the fodder requirements for the animals grazed at  
 210 each experimental plot in a consistent manner. To achieve this, the annual NPP, expressed as  
 211 dry vegetable matter (DM) ( $\text{Mg DM ha}^{-1} \text{y}^{-1}$ ) in terms of C was predicted for each location  
 212 using the Miami model (Lieth, 1972; Grieser et al., 2006), and calculated using mean annual  
 213 precipitation (P, in mm), and mean annual temperature (T, in  $^{\circ}\text{C}$ ) reported in each study or  
 214 determined from the CRU TS 3.4 dataset. (The possible effect of N fertilizer was not  
 215 considered because of data scarcity).

216

$$217 \text{ NPP} = \text{minimum} (\text{NPP}_T; \text{NPP}_P) \quad (5)$$

218

$$219 \text{ NPP}_T = 30 (1 + \exp (1.315 - 0.119 T)) \quad (6)$$

220

$$221 \text{ NPP}_P = 30 (1 - \exp (-0.000664 P)) \quad (7)$$

222

223 where  $\text{NPP}_T$  is the net primary production calculated based upon temperature and  $\text{NPP}_P$  is the  
 224 net primary production calculated based upon precipitation (Lieth, 1972; Grieser et al., 2006).

225

226 The available surface vegetable dry matter (SVDM) available for animal grazing for each  
 227 location was calculated using the following relationship, assuming an allocation of NPP to  
 228 above ground biomass of 50% (Li et al., 1994):

229

$$230 \text{ SVDM} = \text{NPP} \times 0.5 (\text{Mg DM ha}^{-1} \text{y}^{-1}) \quad (8)$$

231

232 An animal unit month (AUM) is considered as a bovine weighing of 500 kg requiring 350 kg  
 233 of DM a month of feed based on the animal equivalent chart (USDA-Animal equivalent  
 234 chart). The carrying capacity (CC) of grassland is the number of animal unit months that the  
 235 land will support, based upon the available forage dry matter and the fodder requirement, and  
 236 this we calculated as:



237

$$238 \quad CC = SVDM / 0.350 \text{ AUM ha}^{-1} \text{ y}^{-1} \quad (9)$$

239

240 The GI was calculated from the ratio of the number of animal unit months actually grazed up  
241 to carrying capacity. The actual number of animal unit months (AAUM) depended on the  
242 type of animal: i) cows =1; ii) steers = 0.7; iii) sheep = 0.2; iv) goats = 0.2, v) domesticated  
243 yaks as 0.7 (USDA-Animal equivalent chart). The AAUM was calculated as the product of  
244 stocking density per ha multiplied by the number of months grazed per year in  $\text{ha}^{-1} \text{ y}^{-1}$ .

245

$$246 \quad GI = AAUM / CC \quad (10)$$

247

248 As changes in SOC stocks are related to the initial SOC and the annual carbon input to the  
249 soil. We calculated the annual carbon input (CIN) to be the quantity of annual NPP carbon  
250 not grazed by the animals, and calculated as:

251

$$252 \quad CIN = NPP (1-GI). \quad (11)$$

253

### 254 *2.3. Data analyses*

255 We used Minitab 17 (Minitab, Inc., State College, PA) to conduct the data exploration,  
256 conditioning and analyses. The complete data set was analysed to estimate the overall impact  
257 of grazing on grassland SOC and selected soil properties, and then to analyse the impact of  
258 climatic zone and GI. We have sufficient data to estimate the change in SOC stock (n=83)  
259 related to grazing for the top 30 cm or the profile over the period of the experiment that could  
260 be normalized to an annual rate per year. For a subset of the data (n=64) it was possible to  
261 estimate the change in total nitrogen per year during the experiment, bulk density change  
262 (n=43) and pH (n=30).

263

264 The data collected were segregated into four climatic zones for the meta-analysis: DC  
265 (n=26), DW (n=33), MC (n=9) and MW (n=15). The data were also grouped by the  
266 calculated GI: low (LG; GI = 0 to 0.33), medium (MG; GI = 0.33 to 0.66), high (HG; GI =  
267 0.66 to 1.0) and overgrazed (OG; GH  $\leq$ 1.0). The tests were also grouped by animal type  
268 bovine (B), which included yaks, steers, cows and heifers; caprine (C), including sheep and  
269 goats; and a mixture of both bovine and caprine (M). The tests were also grouped by soil type  
270 and texture: clay, clay-loam, loam, sandy-loam and sandy; and grassland type: grassland,

271 shrubby grassland, woody grassland, steppe, and prairie. We also tested grass by  
272 photosynthesis type: C3, C4 and mixed.

273

274 We used different analytical procedures for each group and parameter that related to  
275 the available published data. An analysis of the effects of grazing on on SOC, TN, pH and  
276 BD was made by the methods of Hedges et al. (1999) and Luo et al. (2006) using the  
277 response ratio (RR) defined as the natural logarithm of the ratio of the value or the parameter  
278 measured on the grazing treatment to that without grazing (control).

279

$$280 \text{Ln (RR)} = \ln (\text{grazed treatment parameter value/un-grazed (control) parameter value}) \quad (12)$$

281

282 The rate of change (R) was calculated in the form  $\ln (\text{RR})$  by dividing by the length of the  
283 experiment in years (y).

$$284 R = \ln (\text{RR})/y \quad (13)$$

285

286 The descriptive statistics of the annual change in SOC, TN, BD and pH due to grazing  
287 including mean, median, standard deviation, and 95% confidence intervals for each were  
288 calculated. One way ANOVAs were performed to investigate the impact of factors: climate,  
289 GI, grass and animal types on SOC, TN and other selected soil properties, and the rates of  
290 change. Principle component analysis was used to determine significant explanatory variables  
291 and response variables and determine the differences between climate zones. In addition,  
292 regressions or mixed models such as GLM's, were used to determine significant explanatory  
293 variables.

294

### 295 **3. Results**

296

#### 297 *3.1. Estimation of NPP and grazing intensities*

298 Mean NPP for the period 1960-2000 covered a wide range of values reflecting the global  
299 diversity of NPP under different climate zones (Fig. 1). No statistically significant differences  
300 in NPP between the DC, DM and MC climate zones was found; however, the NPP values at  
301 the MW climate were significantly different from those under the other climate zones (Fig. 2  
302 and Table 5). The calculated and reported estimates of GI show considerable overlap, and  
303 only three experiments represented 'overgrazing' i.e. beyond the carrying capacity (Fig. 3).

304 They also illustrated the different definitions of the levels of grazing used in the literature for  
305 each domain.

306

307 A linear regression of annual NPP remaining available as a possible OC input to the  
308 soil, with the calculated GI and climate zones ( $p < 0.001$ ,  $R^2 = 67\%$ ), demonstrated that the  
309 SOC stock under the MC climate zone is much higher than under the other climate zones  
310 (Fig. 4). An ANOVA showed that un-grazed SOC is different between the different climate  
311 zones as shown in Table 6 and explains 21% of the variation. A GLM showed that adding  
312 NPP and pH explained 41% of the un-grazed SOC value.

313

### 314 *3.2. Impacts of grazing intensity on SOC and other selected soil properties using the response* 315 *ratio ln (RR)*

316 An analysis of all studies together and using the response ratio ln (RR) of grazed compared to  
317 un-grazed grassland, showed that GI was associated with a decrease of overall SOC stocks by  
318 a response ratio of -0.0774 (-8%; StDev=0.358). It was also associated with a slight increase  
319 in pH of 0.029 (+3%; StDev=0.044), an increase in TN of 0.06 (+6%; StDev=0.772) and BD  
320 of 0.070 (+7%; StDev=0.083). However, an ANOVA of the SOC, TN, BD and pH showed  
321 that whilst climate zone significantly affects SOC change ( $p = 0.011$ ) and pH ( $p = 0.014$ ), it did  
322 not significantly impact BD ( $p = 0.144$ ) or TN ( $p = 0.118$ ) (Table 7). At all GI levels, grazing  
323 increased SOC stocks under the MW climate (+7.6%), but decreased them under the MC  
324 climate (+19.5%). However, for the DW and DC climates, only the low (+5.8%) and low to  
325 medium (+16.1%) grazing intensities, respectively, led to increases in SOC (Fig. 5).

326

327 Analysis of the impact of animal type (bovine, caprine and mixed) on ln (RR) of SOC  
328 across all climate types showed no significant difference ( $p = 0.89$ ). Neither soil texture (clay,  
329 clay-loam, loam, sandy-loam and sandy) ( $p = 0.75$ ), nor grassland characteristics (grassland,  
330 shrubby grassland, woody grassland, steppe, and prairie) ( $p = 0.079$ ) significantly affected  
331 SOC. However, an ANOVA for grass photosynthesis type (C3, C4 and mixed) showed that  
332 there was a significant difference ( $p = 0.003$ ) with C4 grasslands increasing SOC by 0.056  
333 (StDev=0.341), and C3 grasses and mixed grass decreasing SOC by -0.155 (StDev=0.233)  
334 and -0.25 (StDev=0.435), respectively (Table 8).

335

### 336 *3.3. Impacts of grazing intensity on SOC with annual rate of response ratio ln (RR)*

337 The annual rate of change, R, of the response ratio ln (RR), show that GI overall decreased  
338 SOC, with an annual rate of -0.009 (StDev=0.037), but increased pH at a rate of 0.003  
339 (StDev=0.006), TN at a rate of 0.0005 (StDev= 0.0047) and BD at a rate of 0.009  
340 (StDev=0.021). However an ANOVA of the SOC, TN, BD and pH showed that, whilst  
341 climate zone significantly impacts the rate of SOC change ( $p<0.001$ ), rate of TN ( $p=0.047$ )  
342 and rate of BD change ( $p=0.009$ ), it did not significantly impact the rate of pH change  
343 ( $p=0.201$ ; Table 9). It also showed that GI was associated with more rapid decreases in SOC  
344 in DW and MC climates, than in DC and MW climates (Table 9).

345

#### 346 *3.4. Interactions between climate zone, grazing intensity and soils*

347 The effect of soil texture was tested by ANOVA both for the entire data set ( $n=67$ ) and for  
348 each climatic region (DC,  $n=22$ ; DW,  $n=21$ ; MC,  $n=6$  & MW,  $n=14$ ), but no statistical  
349 differences were found between texture classes (data not shown).

350

#### 351 *3.5. Interactions of significant explanatory variable on response ratio ln (RR).*

352 Principle component analysis (PCA) showed that the main explanatory variables for response  
353 ratio ln (RR) were climate zone, initial SOC, grazing intensity and NPP. PCA component 1-4  
354 derived from this parameter subset showed a different pattern for each climate zone with DW  
355 and DC being similar and MW and MC exhibiting different patterns (Figure 6). When the  
356 contribution of each variable to the four components is examined in radar plots (Figure 7), it  
357 is observed that the pattern of interaction or each variable is different for each climate zone  
358 indicating that SOC change is governed by different factors.

359

## 360 **4. Discussion**

361

#### 362 *4.1. Comparison of methods used here with previous analyses*

363 In this systematic global review and meta-analysis we collected 83 published studies, on the  
364 impacts of GI of grasslands on SOC and other selected soil properties (TN, pH and BD),  
365 covering 164 sites and representing different countries and climatic zones. However, unlike  
366 the previous published reviews (e.g. McSherry and Ritchie, 2013; Lu et al., 2017; Zhou et al.,  
367 2017), we depth-normalized the SOC and TN data in line with IPCC guidelines. We also  
368 calculated a normalized GI. The purpose was to attempt to harmonise very heterogeneous  
369 data. Additionally, the calculation of the normalized GI allowed us to compare across  
370 experiments, since reported grazing intensities were subjective, considering the normal local

371 management practices. We found the calculated GI overlapped with the GI from the collected  
372 literature, which suggests that our normalization method is unlikely to have introduced  
373 additional errors. The extracted mean annual temperatures and annual rainfall at each site  
374 from the CRU 3.4 dataset all agreed well with the values reported in publications, where  
375 given, providing confidence to the calculation of NPP using the Miami model at each  
376 experimental site. Our value of excess NPP for a given GI are similar for all climate zones  
377 except for MW, where the value is almost double that in the other climate zones. Here,  
378 climate, especially temperature and rainfall, influences grass productivity and thereby NPP  
379 (Chu et al., 2016). Climate zones also play a major role in the initial SOC contents, and  
380 values for the different zones were significantly different ( $p < 0.05$ ) from each other (i.e. SOC  
381 was highest for MC, and lowest for the DW climate zone). Estimation of uncertainty is of  
382 crucial importance since it has a large impact on the management decisions. In this study,  
383 some approximations and assumptions incorporated in the methods we used may have  
384 created uncertainty in the final results. To consider this, we have conservatively estimated it  
385 by calculating the standard deviation for all values as shown in the Tables 5-9.

386

#### 387 *4.2. Impacts of grazing intensity on soil organic carbon (SOC)*

388 By pooling all the data and ignoring the regional climatic zones we found that higher GI, was  
389 generally associated with a decrease in SOC stocks. Similar results were found by Lu et al.  
390 (2017) and Zhou et al. (2017) amongst others. However, analysing the data according to  
391 climate zone revealed that the impact of GI on SOC is clearly climate dependent, so that the  
392 same GI level under specific climate zones could have different impacts on SOC compared to  
393 others. This can be explained by the interactions between GI and the environmental  
394 parameters (e.g. temperature and precipitation) at each climate zone. The different GI levels  
395 have significantly different effects on individual plant species occurrences and covers and  
396 thereby, SOC. Generally, grazing stimulates pasture growth, so although the animals under  
397 high GI consume more C from the system and respire it, grazing returns (urine and faeces)  
398 recycle the C, so the input to the soil remains similar. In addition, the amount and quality of  
399 animal urine and dung, and typical manure management practices in each climate zone, may  
400 also stimulate grass regrowth differently. Below we discuss our results for each climate zone  
401 in more detail.

402

##### 403 *4.2.1. Impacts of grazing intensity on soil organic carbon (SOC) under dry/warm climates*

404 Under the DW climate, where soil is dry and temperature and evapotranspiration are high, GI  
405 has detrimental effects on SOC at all levels apart from low GI, under which SOC increases  
406 by 5.8%. In this climate zone, Angassa (2014) reported a decline in species richness under  
407 high GI and suggested low to medium grazing intensities for promoting and conserving key  
408 forage species. Low GI could stimulate grass regrowth and mobilise nutrients within the soil  
409 and therefore, is recommended for steppe-type ecosystems such as those found in Inner  
410 Mongolia (Steffens et al., 2008). Fernandez et al. (2008) reported that high GI affects soil  
411 fertility and has long-term potential implications for the sustainability of grazing in semi-arid  
412 environments. It can also increase CO<sub>2</sub> fluxes from soil and reduce the potential of grasslands  
413 to capture CO<sub>2</sub> by reducing aboveground biomass (Frank et al., 2002), thereby reducing the  
414 source of SOC from above- and below-ground inputs. Similarly, in a mixed prairie, high GI  
415 has been shown to change grass composition (reduced tallgrasses) resulting in reduced litter  
416 accumulation and ground cover (Fuhlendorf et al., 2002). It is also likely to increase nutrient  
417 losses (particularly N) (Craine et al., 2009), affect bacterial and fungal community structures  
418 (Huhe et al., 2017), and hence threaten longer term sustainability . However, according to  
419 Talore et al. (2016), although high GI reduces the total C and total N soil content and its C/N  
420 ratio, a resting period of 1-2 years followed by three consecutive grazing years at low GI  
421 would be ideal for a sustainable livestock production in South Africa. Although Walters et al.  
422 (2017) reported that management of GI, by rotational grazing (which incorporated long  
423 periods of rest) control through fencing increased SOC on red Lixisol soils.

424

#### 425 *4.2.2. Impacts of grazing intensity on soil organic carbon (SOC) under moist/cool climates*

426 In the MC climate zone, where soil is moist for longer periods and the temperature is low, all  
427 type of GIs led to a decrease in SOC. The activity of soil microorganisms is suppressed due to  
428 low temperature and high water saturation of the soil (i.e. reducing oxygen availability). High  
429 rainfall decreases microbial biomass, likely due to high demand of nutrients from the soil for  
430 the peak growth of vegetation during that time (Devi et al., 2014) and decreases soil pH.  
431 Many other studies have found that frequent disturbances of grassland by grazing practices at  
432 different intensities decrease C sequestration in soils (e.g. Klumpp et al., 2007; 2009; Wu et  
433 al., 2009, 2010). Sun et al. (2011) reported that higher GI under alpine meadows, reduced  
434 plant biomass productivity and changed the species composition and thereby, decreased SOC.  
435 Moreover, Wu et al. (2009) and Dong et al. (2012) found that high GI decreased, not only  
436 SOC, but also soil N in the Qinghai-Tibetan Plateau. Further, trampling by cattle decreases  
437 soil carbon storage by stimulating organic matter decomposition, due to the destruction of

438 soil aggregates by mechanical stress, alters soil microbial community structure, leads to lower  
439 fungal to bacterial ratios (Hiltbrunner et al., 2012), and increases denitrification rates and N  
440 losses (Su et al., 2005; Jones et al., 2017). Pappas & Koukoura (2011) found that medium GI  
441 could enhance soil carbon accumulation at higher altitudes. The trade-off between above- and  
442 below-ground C storage is positively associated with net ecosystem productivity. However,  
443 increasing grass productivity by adding more N fertilizer then intensifying the GI accordingly  
444 can increase SOC (Klumpp et al., 2007). Although the use of added N to enhance  
445 productivity in temperate grasslands is widespread, it can lead to an enhancement of N losses  
446 particularly as GI increases. This can lead to a situation where despite increases in C  
447 sequestration the losses of non-CO<sub>2</sub> GHGs increase and the net GHG balance remains close  
448 to zero (or becomes positive), offsetting the benefits of C sequestration (Jones et al., 2017;  
449 Soussana et al., 2007). In circumstances where soils have a high nutrient capital (e.g. upland  
450 sheep grazing), it can be more appropriate to recommend no or low-intensity grazing as a  
451 management practices for enhancing plant and soil C sequestration (Smith et al., 2014). In  
452 contrast, Gao et al. (2007; 2009) and Li et al (2011) reported that higher GI increased soil C  
453 and N storage in alpine meadows through changes in the species composition and biomass  
454 allocation pattern. Although grazing in the warm-season is good for plant diversity  
455 conservation and nutrient storage in the topsoil, whilst grazing in the cold season is suitable  
456 for nutrient storage in deep soil layers (Gao-Lin et al., 2017). Pavlů et al. (2007)  
457 demonstrated that high GI creates canopy gaps, relaxes intra- and inter-specific competition  
458 for light, and ultimately favours the establishment of short-stature, less-palatable forb species.  
459

#### 460 *4.2.3. Impacts of grazing intensity on soil organic carbon (SOC) under moist/warm climates*

461 In the MW climate zone, where both moisture and temperature are high, all GIs have a  
462 beneficial impact on SOC. Temperature increases soil microbial C due to faster  
463 decomposition of plant residues and immobilization of products in the microbial biomass.  
464 However, Devi et al. (2014) found that only medium GI may benefit sub-tropical grasslands,  
465 by influencing nutrient dynamics and could be prescribed for the management of these  
466 grasslands. Da Silva et al. (2014) reported that light GI was a useful management for  
467 enhancing C sequestration whilst high GI led to a reduced number of plants, plant basal area,  
468 and amount of deposited dead plant material. Nevertheless, Wright et al. (2004) reported that  
469 a long-term grazing at low GI of Bermuda-grass pastures can increase SOC and SON  
470 concentrations and could have strong potential for C and N sequestration. This is mainly due  
471 to enhanced turnover of plant material and excreta under low GI. Franzluebbers et al. (2000)

472 found that a long-grazed pastures in the Southern Piedmont USA have great potential to  
473 restore natural soil fertility, sequester soil organic C and N and increase soil biological  
474 activity compared to other land use management. The processing of forage through cattle and  
475 deposition of faeces onto the pasture can increase the long-term storage of SOC  
476 (Franzluebbers et al., 2000). Other studies (e.g. Kieft, 1994; Shrestha and Stahl, 2008) found  
477 no consistent impacts of GI on soil C and N, C/N ratios and microbial biomass and  
478 respiration rate.

479

#### 480 *4.2.4. Impacts of grazing intensity on soil organic carbon (SOC) under dry/cool climates*

481 In the DC climate zone, where both moisture and temperature are low, low to medium GIs  
482 are beneficial for SOC, while high GI impact is unknown as this study found no relevant  
483 published data. According to Ganjegunte et al. (2005) and Han et al. (2008) low to medium  
484 GI is the most sustainable grazing management system to increase SOC. Han et al. (2008)  
485 reported that high GI diminished grass regrowth, decreased litter deposition and decreased  
486 SOC. Steffens et al. (2008) reported that sheep grazing at high GI deteriorated physical and  
487 chemical parameters of steppe top-soils and depleted SOC and could be improved by  
488 reducing GI or excluding from grazing. Further, long-term grazing at different intensity levels  
489 significantly reduced SOC and TN in an Inner Mongolian grassland (Li et al., 2008; Ma et al.,  
490 2016). Also, soil compaction induced by sheep trampling changes selected soil properties and  
491 possibly enhances soil vulnerability to water and nutrient loss, and thereby reduces plant  
492 available water, and thus grassland productivity (Zhao et al., 2007). In contrast, Reeder and  
493 Schuman (2002) found that grazing at high and low intensities increased SOC, partly due to  
494 rapid annual shoot turnover and redistribution of C within the plant-soil system as a result of  
495 changes in plant species composition.

496

#### 497 *4.3. Impacts of grazing intensity on C3/C4 dominated grass or C3-C4 mixed grasslands*

498 Our results show that on average GI was associated with significantly increased SOC for C4  
499 dominated grasslands, whilst it significantly decreased SOC for C3 dominated grasslands and  
500 C3-C4 mixed grasslands. Similar findings were reported by McSherry and Ritchie (2013).  
501 The reason for increased SOC levels under grazed C4-dominated grass, especially in tropical  
502 grasslands, is the ability of the grass to adapt and compensate for grazing practices (Ritchie et  
503 al., 2014). C4 grasses adapt to high GI by having many rhizomes and other storage organs  
504 that enable them to respond quickly to grass defoliation by animals (McNaughton, 1985;  
505 Dubeux et al., 2007). In addition to the warm temperature that encourages macro-



506 decomposers to incorporate plant and animal materials in the soil (Risch et al., 2012), C4-  
507 grasses can compensate the loss by sacrificing stems for leaves (Ziter and MacDougall,  
508 2013), and by containing higher levels of lignin and cellulose (Barton et al., 1976). As C4  
509 dominated grasslands would be generally in the moist warm climate zone these results are  
510 self-consistent.

511

#### 512 *4.4. Impacts of grazing intensity on other selected soil properties (TN, BD and pH)*

513 There were too few data points in each climate zone to assess the impact of grazing intensity  
514 on pH, BD and TN separately for each climate zone. However, pooling data across all climate  
515 zones suggests that on average GI could significantly increase the rate of change of TN and  
516 BD but the effect on soil pH was small. Many studies have found higher BD (e.g. Dong et al.,  
517 2012; Luan et al., 2014; Abril and Bucher, 1999; He et al., 2011) and high pH (e.g. Yong-  
518 Zhong et al., 2005; Pei et al., 2008; Enriquez et al., 2015) in response to high GI in different  
519 climate zones. Grazing intensity increases soil BD and lowers soil moisture content, mainly  
520 due to high animal trampling (He et al., 2011; Zhang et al., 2017), leading to higher  
521 denitrification losses (Oenema et al., 1997) and may increase the risk of soil erosion by wind  
522 (Kolbl et al., 2011). However, some studies have found lower BD due to GI, e.g. Li et al.  
523 (2008) and Schuman et al (1999). High GI was reported to decrease soil pH (Hiernaux et  
524 al.1999; Cui et al. 2005; Zhang et al., 2017). Also, many studies (e.g. Wright et al., 2004;  
525 Ganjegunte et al., 2005; Han et al., 2008; Li et al., 2011) have found that GI increases TN,  
526 while others suggest it decreases TN (e.g. Li et al., 2008; Ma et al., 2016; Zhou et al., 2017)  
527 or had no change (Schuman et al., 1999).

528

### 529 **5. Concluding remarks**

530

531 The impact of GI on SOC stocks differs between the different climate zones, but that lower  
532 GIs increase SOC stocks in three of the four climate zones (list the three here), whereas  
533 higher GIs result in increased SOC in only one climate zone (include the 4<sup>th</sup> here). Although  
534 our model for predicting biomass production does not take into account extra gains in  
535 productivity that can be achieved (promoting increased C sequestration), the benefits (in  
536 terms of net GHG emissions) of N use will often be offset by increased losses of non-CO<sub>2</sub>  
537 GHG emissions (particularly at higher GIs). There are also differences between C3, C4 and  
538 mixed grasslands in their response to GI, and rate of TN change and BD tend to increase  
539 under high GI. The effects of GI management on SOC are mediated by ground cover and

540 high organic matter supply and/or less soil erosion (Waters et al., 2017). High GI can  
541 decrease net primary productivity (Wardle, 2002) and result in the loss of palatable, larger-  
542 leafed species causing domination of unpalatable small-leafed species which produce litter of  
543 low quality for soil microbes and fauna (Cornelissen et al., 1999; Shengjie et al. (2017). This  
544 reduction of some plant-species could also result in decreasing chemical quality of the  
545 organic C stock in soil (Larreguy et al., 2017). Moreover, high GI can shift the  
546 fungal:bacterial ratio towards dominance by fungi, which are more tolerant of periodic  
547 drought and seasonal fluctuations in soil moisture than bacteria (Bagchi and Ritchie, 2010;  
548 Bagchi et al., 2017). Best management practices for GI, therefore, need to be tailored to local  
549 bioclimatic conditions to avoid loss of soil carbon. Policy makers in each climatic zone  
550 should decide on the level of GI depending on the local climate and grass types they have.  
551 Such climate impacts should be considered in future grassland management and conservation  
552 plans. The optimal use of GI and grass species has the potential to significantly increase SOC  
553 and SON sequestration, and alters C and N cycling in soil. In addition, the breeding of plants  
554 with deeper or bushy root ecosystems e.g. *Festulolium* (ryegrass x fescue hybrid), which have  
555 greater efficiency in resource use, could improve carbon storage, water and nutrient retention,  
556 as well as biomass yields (Kell, 2011; Humphreys et al., 2003). In a world of a changing  
557 climate, livestock production will be negatively affected, especially in arid and semiarid  
558 regions, due to e.g. diseases and water availability. Our results have important implications  
559 for setting future grassland management policies that account for climate change. High GI  
560 under increased frequency of drought and heatwave events may increase GHG emissions and  
561 turn grasslands into C sources (Ciais et al., 2005; McSherry and Ritchie, 2013). Additionally,  
562 long-term drought in combination with high atmospheric CO<sub>2</sub> concentration can? decrease  
563 soil microbial biomass and promote a shifts in functional microbial types, and thereby modify  
564 biogeochemical cycles and SOC storage (Barnard et al., 2006; Pinay et al., 2007). Further,  
565 high GI on dry areas or C3 grassland reduces C storage and makes it vulnerable to climate  
566 change, whilst increases C sequestration under C4 grasslands. Thus considering climate will  
567 allow us to properly address sustainability of SOC, conservation of biodiversity, reduction of  
568 greenhouse gas emissions and mitigation of climate change as the geographical location of  
569 the bio-climatic envelope of the flora and fauna of current climatic zones moves with the  
570 evolving climatic disruption.

571

## 572 **Acknowledgements**

573 This work contributes to the N-Circle (grant number BB/N013484/1) and CINAg  
574 (BB/N013468/1) Virtual Joint Centres on Agricultural Nitrogen (funded by the Newton Fund  
575 via UK BBSRC/NERC), U-GRASS (grant number NE/M016900/1), the Belmont  
576 Forum/FACCE-JPI DEVIL project (grant number NE/M021327/1), Soils-R-GGREAT (grant  
577 number NE/P019455/1), ADVENT (grant number NE/M019713/1) and the Scottish  
578 Government's Strategic Research Programme.

579

## 580 **References**

581

- 582 Abril, A., Bucher, E.H., 1999. The effects of overgrazing on soil microbial community and  
583 fertility in the Chaco dry savannas of Argentina. *Appl. Soil Ecol.* 12, 159-167.
- 584 Allard, V., Soussana, J-F., Falcimagne, R., Berbigier, P., Bonnefond, J.M., Ceschia, E.,  
585 D'hour, P., Henault, C., Laville, P., Martin, C., Pinares-Patino, C., 2007. The role of  
586 grazing management for the net biome productivity and greenhouse gas budget (CO<sub>2</sub>,  
587 N<sub>2</sub>O, and CH<sub>4</sub>) of semi-natural grassland. *Agric. Ecosyst. Environ.* 121, 47-58.
- 588 Altesor, A. I., Pineiro, G., Lezama, F., Jackson, R. B., Sarasola, M., Paruelo, J. M., 2006.  
589 Ecosystem changes associated with grazing in sub-humid grasslands of South  
590 America. *J. Veg. Sci.* 17, 323-332.
- 591 Angassa, A., 2014. Effects of grazing intensity and bush encroachment on herbaceous specie  
592 and rangeland condition in southern Ethiopia. *Land degrad. Develop.* 25, 438-451.
- 593 Asgharnezhad, L., Akbarlou, M., Karkaj, E.S., 2013. Influences of Grazing and Enclosure on  
594 Carbon Sequestration *Puccenilia Distans* (Jacq.) Parl. and soil Carbon Sequestration  
595 (Case study: Gomishan wetlands). *Inter. J. Agron. Plant Prod.* 4, 1936-1941.
- 596 Bagchi, S., Roy, S., Maitra, A., Sran, R.S., 2017. Herbivores suppress soil microbes to  
597 influence carbon sequestration in the grazing ecosystem of the Trans-Himalaya.  
598 *Agric. Ecosyst. Environ.* 239,199-206.
- 599 Bagchi, S., Ritchie, M.E., 2010. Introduced grazers can restrict potential soil carbon  
600 sequestration through impacts on plant community composition. *Ecol. Lett.* 13, 959-  
601 968.
- 602 Barnard, R., Barthes, L., Leadley, P.W., 2006. Short-term uptake of 15N by a grass and soil  
603 micro-organisms after long-term exposure to elevated CO<sub>2</sub>. *Plant Soil* 280, 91-99.
- 604 Barger, N.N., Ojima, D.S., Belnap, J., Wang, S., Wang, Y., Chen, Z., 2004. Changes in plant  
605 functional groups, litter quality, and soil carbon and nitrogen mineralization with  
606 sheep grazing in an Inner Mongolian Grassland. *J. Range Manag.* 57,613-619.

607 Barton, F.E., Amos, I.I., H.E., Burdick, D., Wilson, R.L., 1976. Relationship of chemical  
608 analysis to in vitro digestibility for selected tropical and temperate species. *J. Anim.*  
609 *Sci.* 43, 504-512.

610 Cao, J., Yeh, E.T., Holden, N.M., Yang, Y., Du, G., 2013. The effect of enclosures and land-  
611 use contracts on rangeland degradation on the Qinghai-Tibetan plateau. *J. Arid*  
612 *Environ.* 97, 3-8.

613 Chaneton, E. J., Lavado, R. S., 1996. Soil nutrients and salinity after long-term grazing  
614 exclusion in a flooding pampa grasslands. *J. Range Manag.* 49, 182-187.

615 Chu, C., Bartlett, M., Wang, Y., He, F., Weiner, J., Chave, J., Sack, L., 2016. Does climate  
616 directly influence NPP globally? *Glob. Chang. Biol.* 22, 12-24.

617 Ciais, P., Dolman, A. J., Dargaville, R., Barrie, L., Bombelli, A., Butler, J., Canadell, P.,  
618 Moriyama, T., 2010. *Geo Carbon Strategy*, GEO Secretariat, Geneva/FAO, Rome, 48  
619 pp.

620 Ciais, P., Reichstein, M., Viovy, N., et al., 2005. Europe-wide reduction in primary  
621 productivity caused by the heat and drought in 2003. *Nature*, 437, 529-533.

622 Cingolani, A.M., Noy-Meir, I., Diaz, S., 2005. Grazing effects on rangeland diversity: a  
623 synthesis of contemporary models. *Ecol. Appl.* 15, 757-773.

624 Conant, R.T., Paustian, K., Elliott, E.T., 2001. Grassland management and conversion into  
625 grassland: effects on soil carbon. *Ecol. Appl.* 11, 343-355.

626 Conant, R.T., 2012. *Grassland Soil Organic Carbon Stocks: Status, Opportunities,*  
627 *Vulnerability In: R. Lal et al. (eds.), Re-carbonization of the Biosphere: Ecosystems*  
628 *and the Global Carbon Cycle.* Springer Science + Business Media B.V. 2012.

629 Cornelissen, J. H .C., Perez-Harguindeguy, N., Diaz, S., Grime, J. P., Marzano, B., Cabido,  
630 M., Vendramini, F., Cerabolini, B., 1999. Leaf structure and defense control litter  
631 decomposition rate across species and life forms in two regional floras on two  
632 continents. *New Phytol.* 143, 191-200.

633 Craine, J.M., Ballantyne, F., Peel, M., Zambatis, N., Morrow, C., Stock, W.D., 2009. Grazing  
634 and landscape controls on nitrogen availability across 330 South African savanna  
635 sites. *Austr. Ecol.* 34, 731-740.

636 Cui, X.Y., Wang, Y.F., Niu, H.S., Wu, J., Wang, S.P., Schnug, E., Rogasik, J., Fleckenstein,  
637 J., Tang, Y.H., 2005. Effect of long-term grazing on soil organic carbon content in  
638 semiarid steppes in Inner Mongolia. *Ecol. Res.* 20, 519-527.

639 Da Silva, F.D., Amado, T.J.C., Ferreira, A.O., Assmann, J.M., Anghinoni, I., De Faccio

640 Carvalho, P.C., 2014. Soil carbon indices as affected by 10 years of integrated crop-  
641 livestock production with different pasture grazing intensities in Southern Brazil.  
642 *Agri. Ecosyst. Environ.* 190, 60-69.

643 Derner, J.D., J.K. Detling, Antolin, M.F., 2006. Are livestock gains affected by blacktailed  
644 prairie dogs? *Front. Ecol. Environ.* 4, 459-464.

645 Derner, J.D., Schuman, G.E., 2007. Carbon sequestration and rangelands: A synthesis of land  
646 management and precipitation. *J. Soil Water Conserv.* 62, 77-85.

647 Devi, T.I., Yadava, P.S., Garkoti, S.C., 2014. Cattle grazing influences soil microbial  
648 biomass in sub-tropical grassland ecosystems at Nambol, Manipur, north-east India.  
649 *Tropic. Ecol.* 55, 195-206.

650 Dong, S. K., Wen, L., Li, Y. Y., Wang, X. X., Zhu, L., Li, X. Y., 2012. Soil-quality effects  
651 of grassland degradation and restoration on the Qinghai-Tibetan Plateau. *Soil Sci.*  
652 *Soc. Am. J.* 76, 2256-2264.

653 Dubeux, J.C.B., Sollenberger, L.E., Mathews, B.W., Scholberg, J.M., Santos, H.Q., 2007.  
654 Nutrient cycling in warm-climate grasslands. *Crop Sci.* 47, 915-928.

655 Eldridge, D.J., Delgado-Baquerizo, M., Travers, S.K., Val, J., Oliver, I., Hamonts, K., Singh,  
656 B.K., 2017a. Competition drives the response of soil microbial diversity to increased  
657 grazing by vertebrate herbivores. *Ecol.* 98, 1922-1931.

658 Eldridge, D.J., Delgado-Baquerizo, M., 2017b. Continental-scale impacts of livestock grazing  
659 on ecosystem supporting and regulating services. *Land Degrad. Develop.* 28, 1473-  
660 1481.

661

662 Enriquez, A.S., Chimner, R.A., Cremona, M.V., Diehl, P., Bonvissuto, G.L., 2015. Grazing  
663 intensity levels influence C reservoirs of wet and mesic meadows along a precipitation  
664 gradient in Northern Patagonia. *Wet. Ecol. Manag.* 23, 439-451.

665 Fernandez, D.P., Neff, J.C., Reynolds, R.L., 2008. Biogeochemical and ecological impacts of  
666 livestock grazing in semi-arid southern-east Utah, USA. *J. Arid Environ.* 72, 777-791.

667 Frank, A. B., Tanaka, D. L., Hofmann, L., Follett, R. F., 1995. Soil carbon and nitrogen of  
668 northern Great Plains grasslands as influenced by long-term grazing. *J. Range Manag.*  
669 48, 470-474.

670 Frank, D. A., Kuns, M. M., Guido, D. R., 2002. Consumer control of grassland plant  
671 production. *Ecol.* 83, 602-606.

672 Franzluebbers, A.J., Stuedemann, J.A., Schomberg, H.H., Wilkinson, S.R., 2000a. Soil

673 organic C and N pools under long-term pasture management in the Southern  
674 Piedmont, USA. *Soil Biol. Biochem.*32, 469-478.

675 Franzluebbers, A.J., Wright, S.F., Stuedemann, J.A., 2000b. Soil aggregation and glomalin  
676 under pastures in the Southern Piedmont USA. *Soil Soc. Am. J.* 64, 1018-1026.

677 Franzluebbers, A.J., Stuedemann, J.A., 2002. Particulate and non-particulate fractions of soil  
678 organic carbon under pastures in the Southern Piedmont USA. *Environ. Poll.* 116,  
679 S53-S62.

680 Franzluebbers, A.J., Stuedemann, J.A., 2005. Soil carbon and nitrogen pools in response to  
681 tall fescue endophyte infection, fertilization, and cultivar. *Soil Sci. Soc. Am. J.* 69,  
682 396-403.

683 Franzluebbers, A.J., Stuedemann, J.A., 2009. Soil-profile organic carbon and total nitrogen  
684 during 12 years of pasture management in the Southern Piedmont USA. *Agric.*  
685 *Ecosyst. Environ.*129, 28-36.

686 Fuhlendorf, S.D., Zhang, H., Tunnell, T.R., Engle, D.M., Cross, A.F., 2002. Effects of  
687 Grazing on Restoration of Southern Mixed Prairie Soils. *Rest. Ecol.*10, 401-407.

688 Ganjegunte, G.K., Vance, G.F., Preston, C.M., Schuman, G.E., Ingram, L.J., Stahl, P.D.,  
689 Welker, J.M., 2005. Influence of different grazing management practices on soil  
690 organic carbon constituents in a northern mixed-grass prairie. *Soil Sci. Soc. Am. J.*  
691 69, 1746-1756.

692 Gao, Y.H., Luo, P., Wu, N., Chen, H., Wang, G.X., 2007. Grazing intensity impacts on  
693 carbon sequestration in an alpine meadow on the eastern Tibetan Plateau. *Research J.*  
694 *Agric. Biol. Sci.* 3, 642-647.

695 Gao, Y.H., Schuman, M., Chen, H., Wu, N., Luo, P., 2009. Impacts of grazing intensity on  
696 soil carbon and nitrogen in an alpine meadow on the eastern Tibetan Plateau. *J. Food*  
697 *Agric. Environ.* 7, 749-754.

698 Gao-Lin, W., Dong, W., Yu, L., Lu-Ming, D., Zhen-Heng, L., 2017. Warm-season grazing  
699 benefits species diversity conservation and top-soil nutrient sequestration in alpine  
700 meadow. *Land Degrad. Develop.* 28, 1311-1319.

701 Garcia, M.R.L., Sampaio, A.A.M., Nahas, E., 2011. Impact of different grazing systems for  
702 bovine cattle on the soil microbiological and chemical characteristics. *R. Bras.*  
703 *Zootec.* 40, 1568-1575.

704 Ghoreyshi, R., Behjou, F.K., Motamedi, J., Kalanpa, E.G., 2013. Soil carbon capacity in a  
705 grassy rangeland ecosystem in North-western Iran: Implication for conservation.  
706 *Afric. J. Agric. Res.* 8,916-921.

707 Golluscio, R.A., Austin, A.T., Martinez, G.C., Gonzalez-Polo, M., Sala, O.E., Jackson, R.B.  
708 2009. Sheep grazing decreases organic carbon and nitrogen pools in the Patagonian  
709 Steppe: combination of direct and indirect effects. *Ecosyst.* 12, 686-697.

710 Grieser, J., Gommers, R., Bernardi, M., 2006. The Miami Model of climatic net primary  
711 production of biomass. The Agromet Group, SDRN, FAO of the UN, Viale delle  
712 Terme di Caracalla, 00100 Rome, Italy.

713 Hafner, S., Unteregelsbacher, S., Seeber, E., Lena, B., Xu, X., Li, X., Guggenberger, G.,  
714 Miede, G., Kuzyakov, Y., 2012. Effect of grazing on carbon stocks and assimilate  
715 partitioning in a Tibetan montane pasture revealed by  $^{13}\text{C}$  pulse labelling. *Glob.*  
716 *Chan. Biol.* 18, 528-538.

717 Han, G., Hao, X., Zhao, M., Wang, M., Ellert, B.H., Willms, W., Wang, M., 2008. Effect of  
718 grazing intensity on carbon and nitrogen in soil and vegetation in a meadow steppe in  
719 Inner Mongolia. *Agricu. Ecosyst. Environ.* 125, 21-32.

720 Harris, L., Jones, P.D., Osborn, T.J., Lister, D.H., 2013. Updated high resolution grids of  
721 monthly climatic observations - the CRU TS3.1 data set. *Inter. J. Climato.* 34, 623-  
722 642.

723 He, N.P., Zhang, Y.H., Yu, Q et al., 2011. Grazing intensity impacts soil carbon and nitrogen  
724 storage of continental steppe. *Ecosph.* 2, 304-316.

725 Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in  
726 experimental ecology. *Ecol.* 80, 1150-1156.

727 Hiernaux, P., Biélers, C.L., Valentin, C., Bationo A., FernándezRivera, S., 1999. Effects of  
728 livestock grazing on physical and chemical properties of sandy soils in Sahelian  
729 rangelands. *J. Arid Environ.* 41, 231-245.

730 Hiltbrunner, D., Schulze, S., Hagedorn, F., Schmidt, M.W., Zimmermann, S., 2012. Cattle  
731 trampling alters soil properties and changes soil microbial communities in a Swiss  
732 sub-alpine pasture. *Geoderma* 170, 369-377.

733 Huhe, Chen, X., Hou, F., Wu, Y., Cheng, Y., 2017. Bacterial and Fungal Community  
734 Structures in Loess Plateau Grasslands with Different Grazing Intensities. *Front.*  
735 *Microbiol.* 8, 606.

736 Humphreys, M.W., Canter, P. J., Thomas, H. M., 2003. Advances in introgression  
737 technologies for precision breeding within the *LoliumFestuca* complex. *Ann. Appl.*  
738 *Biol.* 143, 1-10.

739 IGBP-DIS, 1998. Soil Data (V.0) A program for creating global soil-property databases,  
740 IGBP Global Soils Data Task, France.

741 Ingram, L.J., Stahl, P.D., Schuman, G.E., et al., 2008. Grazing impacts on soil carbon and  
742 microbial communities in a mixed-grass ecosystem. *Soil Sci. Soc. Am. J.* 72, 939-48.

743 Janzen, H.H., 2006. The soil carbon dilemma: Shall we hoard it or use it? *Soil Biol. Biochem.*  
744 38, 419-424.

745 Jones, M.B., Donnelly, A., 2004. Carbon sequestration in temperate grassland ecosystems  
746 and the influence of management, climate and elevated CO<sub>2</sub>. *New Phytol.* 164, 423-  
747 439.

748 Jones, S.K., Helfter, C., Anderson, M., Coyle, M., Campbell, C., Famulari, D., Di Marco, C.,  
749 van Dijk, N., Topp, C.F.E., Kiese, R., Kindler, R., Siemens, J., Schruppf, M., Kaiser,  
750 K., Nemitz, E., Levy, P., Rees, R.M., Sutton, M.A., Skiba, U.M., 2017. The nitrogen,  
751 carbon and greenhouse gas budget of a grazed, cut and fertilised temperate grassland.  
752 *Biogeosci.* 14, 2069–2088.

753 Kell, D., B., 2011. Breeding crop plants with deep roots: their role in sustainable carbon,  
754 nutrient and water sequestration. *Ann. Bot.* 108, 407-418.

755 Kieft, T.L., 1994. Grazing and plant-canopy effects on semiarid soil microbial biomass and  
756 respiration. *Biol. Fert. Soils* 18, 155-162.

757 Klumpp, K., Soussana, J.-F., Falcimagne, R., 2007. Effects of past and current disturbance on  
758 carbon cycling in grassland mesocosms. *Agric. Ecosyst. Environ.* 121, 59-73.

759 Klumpp, K., Fontaine, S., Attard, E., LeRoux, X., Gleixner, G., Soussana, J.F., 2009. Grazing  
760 triggers soil carbon loss by altering plant roots and their control on soil microbial  
761 community. *J. Ecol.* 97, 876-885.

762 Kölbl, A., Steffens, M., Wiesmeier, M., Hoffmann, C., Funk, R., Krümmelbein, J.,  
763 Reszkowska, A., Zhao, Y., Peth, S., Horn, R., Giese, M., Kögel-Knabner, I., 2011.  
764 Grazing changes topography-controlled topsoil properties and their interaction on  
765 different spatial scales in a semi-arid grassland of Inner Mongolia, P.R. China. *Plant  
766 Soil* 340, 35-58.

767 Lal, R., 2009. Sequestering carbon in soils of arid ecosystems. *Land Degrad. Develop.* 20,  
768 441-444.

769 Larreguy, C., Carrera, A.L., Bertiller, M.B., 2014. Effects of long-term grazing disturbance  
770 on the belowground storage of organic carbon in the Patagonian Monte, Argentina. *J.  
771 Environ. Manag.* 134, 47-55.

772 Larreguy, C., Carrera, A.L., Bertiller, M.B., 2017. Reductions of plant cover induced by



773 sheep grazing change the above-belowground partition and chemistry of organic C  
774 stocks in arid rangelands of Patagonian Monte, Argentina. *J. Environ. Manag.* 199,  
775 139-147.

776 Leith, H., 1972. Modelling the primary productivity of the world. *Nature and Resources*,  
777 UNESCO, VIII, 2, 5-10.

778 Li, C., Frolking, S., Harriss, R., 1994: Modelling carbon biogeochemistry in agricultural  
779 soils. *Glob. Biogeochem. Cycl.* 8, 237-54.

780 Li, C., Hao, X., Zhao, M., Han, G., Willms, W.D., 2008. Influence of historic sheep grazing  
781 on vegetation and soil properties of a Desert Steppe in Inner Mongolia. *Agric.*  
782 *Ecosyst. Environ.* 128, 109-116.

783 Li, W., Huang, H.Z., Zhang, Z.N., Wu, G.L., 2011. Effects of grazing on the soil properties  
784 and C and N storage in relation to biomass allocation in an alpine meadow. *J. Plant*  
785 *Nutr. Soil Sci.* 11, 27-39.

786 Li, X., Zhang, C., Fu, H., Guo, D., Song, X., Wan, C., Ren, J., 2015. Grazing exclusion alters  
787 soil microbial respiration, root respiration and the soil carbon balance in grasslands of  
788 the Loess Plateau, northern China. *Soil Sci. Plant Nutr.* 59, 877-887.

789 Liu, N., Zhang, Y., Chang, S., Kan, H., Lin, L., 2012. Impact of Grazing on Soil Carbon and  
790 Microbial Biomass in Typical Steppe and Desert Steppe of Inner Mongolia. *PLoS*  
791 *ONE* 7, e36434.

792 Luan, J., Cui, L., Xiang, C., Wu, J., Song, H., Ma, Q., et al., 2014. Different grazing removal  
793 enclosures effects on soil C stocks among alpine ecosystems in east Qinghai- Tibet  
794 Plateau. *Ecol. Engen.* 64, 262-268.

795 Luo, Y.Q., Hui, D.F., Zhang, D, Q., 2006. Elevated CO<sub>2</sub> stimulates net accumulations of  
796 carbon and nitrogen in land ecosystems: a meta-analysis. *Ecol.* 87, 53-63.

797 Lu, X., Kelsey, K. C., Yan, Y., Sun, J., Wang, X., Cheng, G., Neff, J. C., 2017. Effects of  
798 grazing on ecosystem structure and function of alpine grasslands in Qinghai-Tibetan  
799 Plateau: a synthesis. *Ecosph.* 8, e01656.

800 Ma, W., Ding, K., Li, Z., 2016. Comparison of soil carbon and nitrogen stocks at grazing-  
801 excluded and yak grazing alpine meadow sites in Qinghai-Tibetan Plateau, China.  
802 *Ecologic. Engineer.* 87, 203-2011.

803 Manley, J.T., Schuman, G.E., Reeder, J.D., Hart, R.H., 1995. Rangeland soil carbon and  
804 nitrogen responses to grazing. *J. Soil Water Conserv.* 50, 294-298.

805 Marriott, C.A., Fisher, G.M., Hood, K., Pakeman, R.J., 2010. Impacts of extensive grazing

806 and abandonment on grassland soils and productivity. *Agric. Ecosyst. Environ.* 139,  
807 476-482.

808 McNaughton, S.J., 1985. Ecology of a grazing ecosystem: The Serengeti. *Ecologic. Monog.*  
809 55: 259-294.

810 McSherry, M., Ritchie, M.E., 2013. Effects of grazing on grassland soil carbon density: a  
811 global review. *Glob. Chan. Biol.* 19, 1347-1357.

812 Medina-Roldana, E., Arredondo, J.T., Huber-Sannwalda, E., Chapa-Vargasa, L., Olalde-  
813 Portugal, V., 2008. Grazing effects on fungal root symbionts and carbon and nitrogen  
814 storage in a shortgrass steppe in Central Mexico. *J. Arid Environ.* 72, 546-556.

815 Medina-Roldan, E., Paz-Ferreiro, J., Bardgett, R. D., 2012 Grazing exclusion affects soil and  
816 plant communities, but has no impact on soil carbon storage in an upland grassland  
817 *Agric. Ecosyst. Environ.* 149 118-23.

818 Naeth, M. A., Bailey A. W., Pluth D. J., Chanasyk, D. S., Hardon R. T., 1991.  
819 Grazing impacts on litter and soil organic matter in mixed prairie and fescue grassland  
820 ecosystems in Alberta. *J. Range Manag.* 44, 7- 12.

821 Neff, J.C., Reynolds, R.L., Belnap, J., Lamothe, P., 2005. Multi-decadal of grazing on soil  
822 physical and biochemical properties in southeast Utah. *Ecol. Appl.* 15, 87-95.

823 Nianpeng, H., Yunhai, Z., Jingzhong, D., Xingguo, H., Taogetao, B., Guirui, Y., 2012. Land-  
824 use impact on soil carbon and nitrogen sequestration in typical steppe ecosystems,  
825 Inner Mong. *J. Geograph. Sci.* 22, 859-873.

826 Niu, D., Hall, S.J., Fu, H., Kang, J., Qin, Y., Elser, J.J., 2011. Grazing exclusion alters  
827 ecosystem carbon pools in Alxa desert steppe. *New Zealand J. Agric. Res.* 54,127-  
828 142.

829 Nosetto, M.D., Jobbagy, E.G., Paruelo, J.M., 2006. Carbon sequestration in semi-arid  
830 rangelands: comparison of *Pinus ponderosa* plantations and grazing exclusion in NW  
831 Patagonia. *J. Arid Environ.* 67,142-156.

832 Oenema, O., Velthof, G.L., Yamulki, S., Jarvis, S.C., 1997. Nitrous oxide emissions from  
833 grazed grassland. *Soil Use Manag.* 13, 288-295.

834 Olf, H., Ritchie, M.E., Prins, H.T.H., 2002. Global environmental controls of  
835 diversity in large herbivores. *Nature*, 415, 901-904.

836 Pappas, I.A., Koukoura Z., 2011. Grazing intensity affects soil carbon sequestration in an  
837 altitudinal gradient. *Dry Grasslands of Europe (ed.): Grazing and Ecosystem Services,*  
838 *Proceedings of 9th European Dry Grassland Meeting (EDGM) Prespa, Greece, 19-23*

839 May 2012-2013 HELLENIC RANGE AND PASTURE SOCIETY (HERPAS) Edited  
840 by: Vrahnakis, M., Kyriazopoulos, A.P., Chouvardas, D., Fotiadis, G.  
841 Pavlů, V., Hejcman, M., Pavlů, L., Gaisler, J. 2007. Restoration of grazing management and  
842 its effect on vegetation in an upland grassland. *Appl. Veget. Sci.* 10, 375-382.  
843 Pei, S., Fu, H., Wan, C., 2008. Changes in soil properties and vegetation following enclosure  
844 and grazing in degraded Alxa desert steppe of Inner Mongolia, China. *Agric. Ecosys.*  
845 *Environ.* 124, 33-39.  
846 Pinay, G., Barbera, P., Carreras-Palou, A., et al., 2007. Impact of atmospheric CO<sub>2</sub> and plant  
847 life forms on soil microbial activities. *Soil Biol. Biochem.* 39, 33-42.  
848 Pineiro, G., Paruelo, J.M., Jobbagy, E.G., Jackson, R.B., Oesterheld, M., 2009. Grazing  
849 effects on belowground C and N stocks along a network of cattle enclosures in  
850 temperate and subtropical grasslands of South America. *Gob. Biogeochem. Cyc.* 23,  
851 GB2003.  
852 Pineiro, G., Paruelo, J.M., Oesterheld, M., Jobbagy, E.G., 2010. Pathways of grazing effects  
853 on soil organic carbon and nitrogen. *Rang. Ecol. Manag.* 63, 109-119.  
854 Powlson, D.S., Whitmore, A.P., Goulding, K.W.T., 2011. Soil carbon sequestration to  
855 mitigate climate change: A critical re-examination to identify the true and the false.  
856 *Euro. J. Soil Sci.* 62, 42-55.  
857 Pringle, M.J., Allen, D.E., Dalal, R.C., Payne, J.E., Mayer, D.G., O'Reagain, P., Marchant,  
858 B.P., 2011. Soil carbon stock in the tropical rangelands of Australia: Effects of soil  
859 type and grazing pressure, and determination of sampling requirement. *Geoderma*  
860 167-168, 261-273.  
861 Qiu, L., Wei, X., Zhang, X., et al., 2013. Ecosystem carbon and nitrogen accumulation after  
862 grazing exclusion in semiarid grassland. *PLoS ONE* 8, e55433.  
863 Raiesi, F., Riahi, M., 2014. The influence of grazing enclosure on soil C stocks and  
864 dynamics, and ecological indicators in upland arid and semi-arid rangelands.  
865 *Ecologic. Indic.* 41, 145-154.  
866 Reeder, J. D., Schuman, G. E., 2002. Influence of livestock grazing on C sequestration in  
867 semi-arid mixed grass and short grass rangelands. *Environ. Pollut.* 116, 457-463.  
868 Reid, R.S., Thornton, P.K., McCrabb, G.J., Kruska, R.L., Atieno, F., Jones, P.G., 2004. Is it  
869 possible to mitigate greenhouse gas emissions in pastoral ecosystems of the tropics.  
870 *Environ. Dev. Sustain.* 6, 91-109.  
871 Reszkowska, A., Krümmelbein, J., Zhao, Y., Peth, S., Horn, R., Gan, L., 2011. Influence of

872 grazing on hydraulic and mechanical properties of semiarid steppe soils under  
873 different vegetation type in Inner Mongolia, China. *Plant Soil* 340, 59-72.

874 Risch, A.C., Anderson, T.M, Schutz, M., 2012. Soil CO<sub>2</sub> emissions associated with  
875 Termitaria in tropical savanna: evidence for hot-spot compensation. *Ecosyst.*15, 1147-  
876 1157.

877 Ritchie, M.E., 2014. Plant compensation to grazing and soil carbon dynamics in a tropical  
878 grassland. *PeerJ*2, e233.

879 Rogers, W. M., Kirby, D. R., Nyren, P. E., Patton, B. D., Dekeyser, E. S., 2005. Grazing  
880 intensity effects on northern plains mixed-grass prairie. *Prairie Natural.* 37, 73-83.

881 Rounsevell, M., Evans, S.P., Bullock, P., 1999. Climate change and agricultural soils:  
882 impacts and adaptation. *Clim. Chan.* 43, 683-709.

883 Russell, J.R., Barnhart, S.K., Morrill, D.G., Sellers, H.J., 2013. Use of mob grazing to  
884 improve cattle production, enhance legume establishment and increase carbon  
885 sequestration in Iowa pastures. *Leopold Centre Completed Grant Reports.*433.  
886 [http://lib.dr.iastate.edu/leopold\\_grantreports/433](http://lib.dr.iastate.edu/leopold_grantreports/433)

887 Schonbach, P., Wolf, B., Dickhofer, U., Wiesmeier, M., Chen, W., Wan, H., et al. 2012.  
888 Grazing effects on the greenhouse gas balance of a temperate steppe ecosystem. *Nutr.*  
889 *Cycl. Agroecosyst.* 93, 357-371.

890 Schuman, G.E., Reeder, J.D., Manley, J.T., Hart, R.H., Manley, W.A., 1999. Impact of  
891 grazing management on the carbon and nitrogen balance of a mixed-grass rangeland.  
892 *Ecol. Applic.* 9, 65-71.

893 Schuman, G. E., Janzen, H. H., Herrick J. E., 2002. Soil carbon dynamics and potential  
894 carbon sequestration by rangelands. *Environ. Poll.* 116, 3: 391-396.

895 Schuman, G.E., Ingram, L.J., Stahl, P.D., Derner, J.D., Vance, G.F., Morgan, J.A., 2009.  
896 Influence of Management on Soil Organic Carbon Dynamics in Northern Mixed-  
897 Grass Rangeland. *Soil Carbon Sequestration and the Greenhouse Effect*, 2nd edition.  
898 SSSA Special Publication 57. ASA-CSSA-SSSA, 677 S. Segoe Rd., Madison, WI  
899 53711, USA.

900 Scurlock, J. M. O., Hall, D. O., 1998. The global carbon sink: A grassland perspective', *Glob.*  
901 *Chan. Biol.* 4, 229-233.

902 Shengjie, L.I.U., Xiaodong, Y., IVES, A.R., Zhili, F., Liqing, S.H.A., 2017. Effects of  
903 Seasonal and Perennial Grazing on Soil Fauna Community and Microbial Biomass  
904 Carbon in the Subalpine Meadows of Yunnan, Southwest China. *Pedosph.* 27, 371-  
905 379.

906 Shrestha, G., Stahl, P.D., 2008. Carbon accumulation and storage in semi-arid sagebrush  
907 steppe: effects of long-term grazing exclusion. *Agric. Ecosyst. Environ.* 125, 173-181.

908 Silveira, M.L., Xu, S., Adewopo, J., Franzluebbbers, A.J., Buonad, G., 2014. Grazing land  
909 intensification effects on soil C dynamics in aggregate size fractions of a Spodosol.  
910 *Geoderma* 230-231, 185-193.

911 Smith, P., Goulding, K.W.T., Smith, K.A., Powlson, D.S., Smith, J.U., Falloon, P., Coleman,  
912 K., 2000. Including trace gas fluxes in estimates of the carbon mitigation potential of  
913 UK agricultural land. *Soil Use Manag.* 16, 251-259.

914 Smith, P., Martino, D., Cai, Z., et al., 2008. Greenhouse gas mitigation in agriculture.  
915 *Philosophical Transactions of the Royal Society B: Biologic Sci.* 363, 789-813.

916 Smith, S. W., Vandenberghe, C., Hastings, A., Johnson, D., Pakeman, R., Wal, R., Woodin,  
917 S.J., 2014. Optimizing carbon storage within a spatially heterogeneous upland  
918 grassland through sheep grazing management. *Ecosyst.* 17, 418-429.

919 Sigua, G.C., Coleman, S.W., Albano, J., 2009. Quantifying soil organic carbon in forage-  
920 based cow-calf congregation-grazing zone interface. *Nutr. Cycl. Agroecosyst.* 85,  
921 215-223.

922 Soussana, J. F., Allard, V., Pilegaard, K., Ambus, P., Amman, C., Campbell, C., Ceschia, E.,  
923 Clifton-Brown, J., Czobel, S., Domingues, R., Flechard, C., Fuhrer, J., Hensen, A.,  
924 Horvath, L., Jones, M., Kasper, G., Martin, C., Nagy, Z., Neftel, A., Raschi, A.,  
925 Baronti, S., Rees, R. M., Skiba, U., Stefani, P., Manca, G., Sutton, M., Tuba, Z., and  
926 Valentini, R, 2007. Full accounting of the greenhouse gas (CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>) budget of  
927 nine European grassland sites. *Agric. Ecosyst. Environ.* 121, 121-134.

928 Steffens, M., Kolbl, A., Totsche, K.U., Kogel-Knabner, I., 2008. Grazing effects on soil  
929 chemical and physical properties in a semiarid steppe of Inner Mongolia (PR China).  
930 *Geoderma* 143, 63-72.

931 Sun, D.S., Wesche, K., Chen, D.D., Zhang, S.H., Wu, G.L., et al., 2011. Grazing depresses  
932 soil carbon storage through changing plant biomass and composition in a Tibetan  
933 alpine meadow. *Plant Soil Environ.* 57, 271-278.

934 Talore, D.G., Tesfamariam, E.H., Hassen, A., Du Toit, J.C., Klamppd, K., Jean-Francoise, S.,  
935 2016. Long-term impacts of grazing intensity on soil carbon sequestration and  
936 selected soil properties in the arid Eastern Cape, South Africa. *J. Sci. Food Agric.* 96,  
937 1945-52.

938 Teague, W.R., Dowhower, S.L., Baker, S.A., Haile, N., DeLaune, P.B., Conover, D.M.,

939 2011. Grazing management impacts on vegetation, soil biota and soil chemical,  
 940 physical and hydrological properties in tall grass prairie. *Agric. Ecosyst. Environ.*  
 941 141, 310-322.

942 Tessema, Z.K., de Boer, W.F., Baars, R.M.T., Prins, H.H.T., 2011. Changes in soil nutrients,  
 943 vegetation structure and herbaceous biomass in response to grazing in a semi-arid  
 944 savanna of Ethiopia. *J. Arid Environ.* 75, 662-670.

945 Thomas, A.D., 2012. Grasslands in southern Botswana organic carbon and soil CO<sub>2</sub> efflux in  
 946 two semiarid Impact of grazing intensity on seasonal variations in soil. *Phil. Trans. R.*  
 947 *Soc. B* (2012) 367, 3076-3086.

948 USDA. Animal equivalent chart - Domestic Livestock, Native Wildlife and Exotic Wildlife.  
 949 [shttps://www.nrcs.usda.gov/Internet/FSE\\_DOCUMENTS/nrcs144p2\\_002433.pdf](https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_002433.pdf)  
 950 (accessed 31-Aug-2017).

951 Wang, W., Fang, J., 2009. Soil respiration and human effects on global grasslands. *Glob.*  
 952 *Planet. Chan.* 67, 20-28.

953 Wang, Y., Heberling, G., Gorzen, E., Mieke, G., Seeber, E., Wesche, K., 2017. Combined  
 954 effects of livestock grazing and abiotic environment on vegetation and soils of  
 955 grasslands across Tibet. *Appl. Veg. Sci.* 20, 327-339.

956 Wang, Z., Jiao, S., Han, G., Zhao, M., Ding, H., Zhang, X., Wang, X., Ayers, E.L., Willms,  
 957 W.D., Havsatad, K., Lata, A., Liu, Y., 2014. Effects of Stocking Rate on the  
 958 Variability of Peak Standing Crop in a Desert Steppe of Eurasia Grassland. *Environ.*  
 959 *Manag.* 53, 266-273.

960 Wardle, D. A., 2002. *Communities and Ecosystems: Linking the Above ground and*  
 961 *Belowground Components.* Princeton University Press, Princeton.

962 Waters, C.M., Orgill, S.E., Melville, G.J., Toole, I.D., Smith, W.J., 2017. Management of  
 963 grazing intensity in the semi-arid rangelands of southern Australia: effects on soils  
 964 and biodiversity. *Land Degrad. Develop.* 28, 1363-1375.

965 Wright, I. J., Reich, P. B., Westoby, M., Ackerly, D. D., Baruch, Z., Bongers, F.,  
 966 CavenderBares, J., Chapin, T., Cornelissen, J. H. C., Diemer, M., Flexas, J., Garnier,  
 967 E., Groom, P. K., Gulias, J., Hikosaka, K., Lamont, B. B., Lee, T., Lee, W., Lusk, C.,  
 968 Midgley, J. J., Navas, M. L., Niinemets, U., Oleksyn, J., Osada, N., Poorter, H., Poot,  
 969 P., Prior, L., Pyankov, V. I., Roumet, C., Thomas, S. C., Tjoelker, M. G., Veneklaas,  
 970 E. J., and Villar, R., 2004. The worldwide leaf economics spectrum. *Nature* 428, 821-  
 971 827.

972 Wu, L., He, N., Wang, Y., Han, X., 2008. Storage and dynamics of carbon and nitrogen in

973 soil after grazing exclusion in *Leymus chinensis* grasslands of northern China. J.  
974 Environ. Qual. 37, 663-668.

975 Wu, G.L., Du, G.Z., Liu, Z.H., Thirgood, S., 2009. Effect of fencing and grazing on a  
976 Kobresia-dominated meadow in the Qinghai-Tibetan Plateau. Plant Soil 319,115-126.

977 Wu, G.L., Liu, Z.H., Zhang, L., Chen, J.M., Hu, T.M., 2010. Longterm fencing improved soil  
978 properties and soil organic carbon storage in an alpine swamp meadow of western  
979 China. Plant Soil 332, 331-337.

980 Xie, Y., Wittig, R., 2004. The impact of grazing intensity on soil characteristics of *Stipa*  
981 *grandis* and *Stipa bungeana* steppe in northern China (autonomous region of Ningxia).  
982 Acta Oecol. 25, 197-204.

983 Xu, M.Y., Xie, F., Wang, K., 2014. Response of Vegetation and Soil Carbon and Nitrogen  
984 Storage to Grazing Intensity in Semi-Arid Grasslands in the Agro-Pastoral Zone of  
985 Northern China. PLoS ONE 9, e96604.

986 Yi, W., Wen-Xia, D., Tu, C., Washburn, S., Lei, C., Hu, S., Soil Carbon, Nitrogen and  
987 Microbial Dynamics of Pasturelands: Impacts of Grazing Intensity and Planting  
988 Systems. Pedosph. 24, 408-416.

989 Yong-Zhong, S., Yu-Lin, L., Jian-Yuan, C., Wen-Zhi, Z., 2005. Influences of continuous  
990 grazing and livestock exclusion on soil properties in a degraded sandy grassland,  
991 Inner Mongolia, northern China. Catena 59, 267-278.

992 Zhang, J., Zuo, X., Zhou, X., Lv, P., Lian, J., Yue, X., 2017. Long-term grazing effects on  
993 vegetation characteristics and soil properties in a semiarid grassland, northern China.  
994 Environ. Monit. Assess. 189, 216.

995 Zhao, Y., Peth, S., Krummelbein, J., Horn, R., Wang, Z., Steffens, M., Hoffmann, C., Peng,  
996 X., 2007. Spatial variability of soil properties affected by grazing intensity in Inner  
997 Mongolia grassland. Ecol. Model. 205, 241-254.

998 Zhou, G., Zhou, X., He, Y., Shao, J., Hu, Z., Liu, R., Zhou, H., Hosseinibai, S.,  
999 2017. Grazing intensity significantly affects belowground carbon and nitrogen cycling  
1000 in grassland ecosystems: a meta-analysis. Glob. Chan. Biol. 23, 1167-1179.

1001 Ziter, C., MacDougall, A.S., 2013. Nutrients and defoliation increase soil carbon inputs in  
1002 grassland. Ecol. 94,106-116.

1003 Zuo, X.A., Zhao, H.L., Zhao, X.Y., Zhang, T.H., Guo, Y.R., Wang, S.K., Drake, S., 2008.  
1004 Spatial pattern and heterogeneity of soil properties in sand dunes under grazing and  
1005 restoration in Horqin Sandy Land, Northern China. Soil Till. Res. 99, 202-212.

1006