

Scotland's Rural College

The impact of ploughing intensively managed temperate grasslands on N₂O, CH₄ and CO₂ fluxes

Drewer, J; Anderson, M; Levy, PE; Scholtes, B; Helfter, C; Parker, J; Rees, RM; Skiba, UM

Published in:
Plant and Soil

DOI:
[10.1007/s11104-016-3023-x](https://doi.org/10.1007/s11104-016-3023-x)

First published: 19/08/2016

Document Version
Peer reviewed version

[Link to publication](#)

Citation for published version (APA):

Drewer, J., Anderson, M., Levy, PE., Scholtes, B., Helfter, C., Parker, J., Rees, RM., & Skiba, UM. (2016). The impact of ploughing intensively managed temperate grasslands on N₂O, CH₄ and CO₂ fluxes. *Plant and Soil*, 411(1), 193 - 208. <https://doi.org/10.1007/s11104-016-3023-x>

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 *GHG fluxes after ploughing*

2 **The impact of ploughing intensively managed temperate grasslands on**
3 **N₂O, CH₄ and CO₂ fluxes**

4 J. Drewer^a, M. Anderson^a, P.E. Levy^a, B. Scholtes^b, C. Helfter^a, J. Parker^b, R.M. Rees^b, U.M.
5 Skiba^a

6 ^a*CEH, Bush Estate, Penicuik, EH26 0QB, Scotland, UK*

7 ^b*SRUC, West Mains Road, Edinburgh, EH9 3JG Scotland, UK*

8

9 Correspondence:

10 Julia Drewer

11 NERC Centre for Ecology and Hydrology

12 Bush Estate

13 Penicuik

14 EH26 0QB

15 Tel. +44 131 4454343

16 Fax. +44 131 4453943

17 juew@ceh.ac.uk

18

19 **Keywords**

20 Ploughing, N₂O, CH₄, CO₂, grassland, temperate climate, tillage

21 **Abstract**

22

23 *Background and aims*

24 Temperate grasslands are a globally important component of agricultural production systems
25 and a major contributor to the exchange of greenhouse gases (GHG) between the biosphere
26 and atmosphere. Many intensively managed grazed grasslands in NW Europe are ploughed
27 and reseeded occasionally in order to improve their productivity. Here, we examined the
28 impact of ploughing on the emission of GHGs a grassland.

29 *Methods*

30 To study these interactions we measured soil GHG fluxes using the static chamber method in
31 addition to the net ecosystem exchange (NEE) of CO₂ by eddy covariance from two adjacent
32 fields. Until ploughing one field in 2012 and the other in 2014, management of these
33 intensively grazed grasslands was almost the same and typical for the study region.

34 *Results*

35 The effect on N₂O is small, but distinguishable from the effects of N fertilisation, soil
36 temperature and soil moisture. Tillage-induced N₂O fluxes were close to expectations based
37 on the IPCC default methodology. By far the dominant effect on the GHG balance was the
38 temporary reduction in GPP.

39 *Conclusions*

40 Ploughing and reseeded can substantially influence short-term GHG emissions. Therefore
41 tillage-induced fluxes ought to be considered when estimating greenhouse gas fluxes or
42 budgets from grasslands that are periodically ploughed.

43

44 **Introduction**

45 Grasslands rank among the world's most extensive ecosystems and are used for forage
46 production and animal grazing (Campbell and Stafford Smith 2000). They cover 22% of the
47 EU-25 land area, accounting for 80 million ha (EEA 2005). Managed grasslands are major
48 source of emissions of N₂O, CO₂ and CH₄, if grazed by ruminants. Emission rates depend on
49 soil management, soil type, climate and interannual climate variability (Skiba et al, 2012,
50 Jones et al. 2005).

51

52 In order to maintain high harvest yields and optimal grass growth for grazing, renovation
53 activities, such as ploughing and harrowing, are periodically carried out on intensively
54 managed grasslands. To maximise productivity, these grasslands are heavily fertilised and
55 therefore known large sources of N₂O (Davies et al. 2001, Soussana et al, 2007).

56

57 Tillage is defined as the mechanical manipulation of soil conditions to support crop
58 production, including ploughing and harrowing operations (Brady and Weil 2002).
59 Depending on local soil properties and weather patterns, grassland tillage can increase grass
60 yield and improve soil structure and aeration through drainage, which is often necessary in
61 order to maintain productivity. On the other hand, this mechanical agitation is known to
62 change soil properties and thereby can affect the net GHG exchange of grasslands (Ball et al.
63 2014).

64

65 Pagliai et al. (2004) showed that soil porosity can decrease under conventionally tilled loam
66 soils, and by reducing the size and the continuity of pores, water conductivity decreases.
67 Conventional tillage (particularly in wet soils) can increase subsoil compaction, promoting
68 conditions that are associated with increased rates of denitrification (Uchida et al. 2008). On

69 the other hand, conventional tillage can be beneficial for certain soil types, such as poorly
70 drained and compactable soils (Ball et al. 1999). Other studies reported that long-term
71 ploughing practices resulted in soil organic matter (SOM) losses (Eriksen and Jensen 2001),
72 microbial biomass and water-stable aggregation decrease as well as lower potentially
73 mineralisable N (Karlen et al. 2013). Generally, the impact on ploughing on soil properties
74 depends on the soil type and weather conditions, thus resulting in many contrasting reports in
75 the literature (Soane et al. 2012). Ball et al. (1999) reported that high rates of N₂O emissions
76 were mainly associated with rainfall patterns and compact arable soils, and no strong
77 correlation between soil tillage and N₂O emissions was found. In contrast, Kessavalou et al.
78 (1998) found a 100% increase in N₂O emissions from a loam soil after a tillage event during
79 fallow, which agrees with other studies (Estavillo et al. 2002). For poorly drained grasslands,
80 conventional tillage can be used as a mitigation method to increase soil porosity and water
81 infiltration. As a consequence, denitrification rates can decrease and N₂O emissions are
82 reduced (MacDonald et al. 2011).

83

84 We report detailed data which allowed comparison of the effect of ploughing on GHG
85 exchange at the long-term field study site, Easter Bush, South East Scotland. Two adjacent,
86 predominately sheep grazed grasslands under the same management, were ploughed two
87 years apart and thereby provided the opportunity to evaluate the magnitude of ploughing-
88 induced GHG fluxes. This was not a designed experiment, but reflects common farming
89 practice in this region, and can therefore provide useful information directly relevant to this
90 kind of land management.

91 Our questions were:

92 (1) Do ploughing and associated management operations increase N₂O, CH₄ and CO₂
93 fluxes?

94 (2) How variable are ploughing-induced emissions?

95

96 **Materials and Methods**

97 *Site description*

98 The study site is located at Easter Bush, 10 km south of Edinburgh, Scotland, in a
99 mesothermal maritime climate (latitude 55°52'N, longitude 3°2'W). The two adjacent fields
100 (North Field (NF) and South Field (SF)) are managed grasslands (>90% *Lolium perenne*).
101 The soil is an imperfectly drained sandy clay loam (FAO classification: eutric cambisol) with
102 a clay content varying from 20 - 26% and a pH varying from 5 to 6 (in H₂O), depending
103 when the soil was last limed. Soils were limed prior to the ploughing in 2012 and the soil pH
104 was 6.1 (in H₂O) during the 2012 - 2014 study period. During extended periods of rain, these
105 fields tend to have localised waterlogging due to an insufficient drainage system. A
106 meteorological station positioned between these two fields provides continuous
107 measurements, with data averaged over 30 min periods. Rainfall amount is measured using a
108 tipping bucket and air temperature at a height of 1.5 m above ground. The 10 year mean (1
109 Jan 2004 – 31 Dec 2014) air temperature was 8.8 °C and rainfall 958 mm with a variation of
110 less than 100 mm from the 10-year mean.

111

112 Agronomic management of both fields was very similar. In the 10 years prior to the
113 ploughing experiment, the fields were predominately grazed by sheep and occasionally, for
114 short periods, by cattle in 2004-2006, and on the NF in August and September 2012.
115 Livestock was sporadically removed from the fields for periods of several days up to several
116 weeks. The 10 year average livestock density was 0.84 LSU ha⁻¹ y⁻¹, cattle contributed only
117 with 0.05 LSU ha⁻¹ y⁻¹. In order to maintain high grass yields, the fields receive mineral N
118 fertiliser, mainly as ammonium nitrate (NH₄NO₃), but occasionally as NPK compound

119 fertiliser or urea. The 10 year average nitrogen (N) fertiliser application rate was 194 kg N ha⁻¹
120 y⁻¹, usually split across three applications during spring and early summer months (Skiba et
121 al. 2013).

122

123 Foregoing ploughing and reseeded the grass was killed using Glyphosate (Table 1). The
124 South field (SF) and the North field (NF) were ploughed on 1st May 2012 and on 20th May
125 2014, respectively, with a mouldboard plough to a depth of 30 cm. The fields were harrowed,
126 reseeded and rolled a few days after both ploughing events. All management operations and
127 fertiliser applications during the study periods in both years are summarised in Table 1 and
128 the management operations were essentially identical for the two years. It is common practice
129 not to apply N fertiliser until the grass is well established. Therefore only the NF received N
130 fertiliser on the 28th of May 2012, and only the SF was fertilised on the 9th May 2014. In
131 2012 GHG flux measurements were made for 39 days before ploughing and 142 days after
132 ploughing and in 2014 a shorter study provided the same measurements for 67 days before
133 ploughing and 34 days after ploughing.

134

135 *Measurements of soil N₂O, CH₄ and CO₂ fluxes*

136 The static chamber method (Clayton et al. 1994) was used for N₂O and CH₄ flux
137 measurements. Round static chambers (diameter = 40 cm) consisting of opaque
138 polypropylene bases, were installed on each field; 20 (10 in each field) in 2012 and 10 (5 in
139 each field) in 2014, respectively. The bases of 10 cm height were inserted into the ground to a
140 depth of approximately 5 cm for the entire study period to allow free grazing. Lids of 20 cm
141 height, were fastened onto the bases using four strong clips, only during the 60 minute
142 measurement periods. A strip of commercially available draft excluder glued onto flange of
143 the lid provided a gas tight seal between chamber and lid. The lids were fitted with a pressure

144 compensation plug to maintain ambient pressure in the chambers during and after sample
145 removal. Gas samples were taken at regular intervals over one hour (0, 30, 60 min in 2012
146 and 0, 20, 40, 60 min in 2014) for each chamber. A three way tap was used for gas sample
147 removal using a 100 ml syringe. 20 ml glass vials were filled with a double needle system to
148 flush the vials with five times their volume. The samples and three sets of four certified
149 standard concentrations (N₂O, CH₄, CO₂ in N₂ with 20% O₂) were analysed at CEH on an
150 HP5890 Series II gas chromatograph (Hewlett Packard (Agilent Technologies) UK Ltd.,
151 Stockport, UK) with electron capture detector (ECD) for N₂O analysis and flame ionization
152 detector (FID) for CH₄ analysis. These detectors were setup in parallel allowing the analysis
153 of the two GHGs at the same time. Limit of detection was 7 ppb for N₂O and 0.07 ppm for
154 CH₄. Peak integration was carried out with Clarity chromatography software (DataApex,
155 Prague, Czech Republic). The flux F ($\mu\text{g m}^{-2} \text{s}^{-1}$) for each sequence of gas samples from the
156 different chambers was calculated according to Equation 1:

157

$$158 \quad F = \frac{dC}{dt} \times \frac{\rho V}{A} \quad (\text{Equation 1})$$

159

160 Where $\frac{dC}{dt}$ is the concentration (C , $\mu\text{mol mol}^{-1}$) change over time (t , in s), which was
161 calculated by linear regression.

162 $\frac{\rho V}{A}$ is the number of molecules in the enclosure volume to ground surface ratio, where ρ is the
163 density of air (mol m^{-3}),

164 V (m^3) is the air volume in the chamber and

165 A (m^2) is the surface area in the chamber (Levy et al. 2012).

166

167 In addition, ecosystem CO₂ respiration rates, which is the sum of soil and vegetation CO₂
168 respiration, were measured close to each chamber location using an opaque closed dynamic

169 chamber (volume: 0.001171 m³) covering 0.0078 m² of soil for 120 s with an EGM-4
170 infrared gas analyser (IRGA: InfraRed Gas Analyser) (PP Systems; Hitchin, Hertfordshire,
171 England). Taking into account the soil temperature, fluxes were calculated based on the linear
172 increase of CO₂ concentrations. In 2012, the short-term physical release of CO₂ immediately
173 after ploughing the SF was investigated from 4 random locations. First soil respiration
174 measurements were made within 10 – 19 minutes after the plough turned the soil over and
175 were repeated at intervals up to almost 3 hours. Thereafter CO₂ respiration rates (bulk soil
176 and vegetation), were always measured at approximately the same time and adjacent to the
177 chambers used for N₂O and CH₄ flux measurements, both in 2012 and 2014.

178

179 *Auxiliary physical and chemical soil measurements*

180 Other environmental parameters were measured during time of chamber enclosure as possible
181 explanatory variables for correlation with recorded GHG fluxes. Soil temperature was
182 measured with a handheld Omega HH370 temperature probe (Omega Engineering UK Ltd.,
183 Manchester, UK) for each chamber location at a depth of 10 cm. Volumetric soil moisture
184 content (VSM) was measured at a depth of 7 cm with a handheld Theta probe HH 2 moisture
185 meter (Delta T-Devices, Cambridge, UK) horizontally inserted at four points around each
186 chamber. Gravimetric moisture content (GWC) was occasionally measured to calibrate the
187 Theta probes. In order to determine bulk density, total C/N, ammonium (NH₄⁺) and nitrate
188 (NO₃⁻) concentrations, soil cores were taken around each of the chamber locations. Soil
189 samples for determination of bulk density were collected using a galvanised iron ring (98.17
190 cm³) with a sharp edge that was inserted in the upper soil layer with a hammer to 5 cm depth
191 without compaction. Samples were oven-dried at 105 °C until constant weight (usually 48
192 hours) and bulk density (g cm⁻³) was calculated based on the dry weight occupying the
193 volume of the ring.

194

195 For NH_4^+ and NO_3^- analysis 15 g of fresh soil was mixed in plastic flasks with 50 ml of 1 M
196 KCl solution made up with deionised water. The flasks were put on a Stuart Orbital Shaker
197 SSL1 (Barloworld Scientific Ltd., Stone, UK) set to 100 rpm for 1 hour. The extract was
198 filtered with Whatman 42 filter papers and poured into vials that were stored frozen
199 thereafter. Defrosted samples were then analysed with a SAN++ Automated Wet Chemistry
200 Analyzer (Skalar Analytical B.V., Breda, Netherlands). To determine total soil C and N,
201 samples were oven-dried at 105°C and ground with a mixer mill MM200 (Retsch GmbH &
202 Co. KG, Haan, Germany) at CEH. Between 10 and 20 mg of each soil sample was transferred
203 to tin capsules and analysed together with four standards of aspartic acid with a Flash 2000
204 Elemental Analyzer (Thermo Fisher Scientific, Cambridge, UK).

205

206 *Net ecosystem exchange of CO_2*

207 In addition to the above described ecosystem respiration rates, we measured the net
208 ecosystem exchange of CO_2 . In order to measure from the ploughed and unploughed fields
209 simultaneously we installed a mobile eddy covariance (EC) system in addition to our
210 permanent, long-term system, in both years.

211

212 *Long-term eddy-covariance system*

213 Fluxes of CO_2 have been measured continuously by eddy-covariance (EC) at Easter Bush
214 since 2002. The EC mast is located along the fence line which separates the NF from the SF
215 (Figure 1). The EC system consists of a Gill WindmasterPro ultrasonic anemometer for the
216 measurement of 3D wind vector components and sonic temperature (20 Hz data), and of a
217 LICOR 7000 closed-path infrared gas analyser (IRGA) operating at 10 Hz for the
218 simultaneous measurement of CO_2 and H_2O mole fractions. Air is sampled at 10 l min^{-1} , 20

219 cm below the mid-point between the anemometer's transducers (effective measurement
220 height of 2.5 m) through a 10 m long Dekabon© line (OD ¼"). Data is captured and
221 processed offline into half-hourly fluxes using in-house software written in LabView™
222 (National Instruments). Data capture was high in the period 9th May - 20th Aug 2012 (85%),
223 with a 52% to 48% split between measured fluxes originating from the SF and the NF
224 respectively. The extent of the flux footprint of the long-term EC system during the 2012
225 measurement period relevant to the ploughing experiment is shown in Figure 1. The footprint
226 statistics used for this figure were obtained with the analytical Kormann-Meixner footprint
227 model for non-neutral stratification (Kormann and Meixner 2001). In 2014, total data capture
228 after filtering was 84% for the long-term EC system with a 71% to 29% split between
229 measured fluxes originating from the SF and the NF respectively.

230

231 *Mobile eddy covariance system in 2012*

232 The prevailing wind direction pre- and post-ploughing was from the N/NW and not the usual
233 S/SE. This means that the long-term EC system mainly measured CO₂ fluxes from the
234 unploughed grassland in the NF. Therefore a temporary mast was erected in the SF in April
235 2012 (Figure 1) to achieve the direct temporal comparison of F_{CO₂} from the ploughed and
236 unploughed field for wind directions in the range ~ N-NW to N-NE. The SF system was a
237 Campbell Scientific EC150 open-path infrared gas analyser for CO₂ and H₂O combined with
238 a Campbell CSAT3 ultrasonic anemometer, with effective measurement height of 1.90 m.
239 Data were logged at 20 Hz to a Campbell Scientific CR3000 data logger and processed
240 offline. The SF system provided 3245 half-hourly average flux in total in the period 9th May -
241 20th Aug 2012 (66% of possible half-hourly data points during this measuring period), of
242 which 926 (28%) corresponded to wind directions in the range ~ N-NW to N-NE. Low
243 turbulence ($u_* < 0.1 \text{ m s}^{-1}$) and periods of rain accounted for over 95% of missing data.

244

245 *Mobile eddy covariance system in 2014*

246 The prevailing wind direction was SE and the above mentioned long-term eddy covariance
247 system provided the measurements for the SF (which in 2014 was the newly established grass
248 sward, after ploughing in 2012). A mobile system, different to the mobile system used in
249 2012, was erected in the NF in May 2014 prior to the ploughing of the field on 20th May
250 2014 (Figure 1) and was removed on 4th Aug 2014. The EC system consisted of a Metek
251 USA-1 ultrasonic anemometer operating at 20 Hz and a Licor 7000 closed-path infrared gas
252 analysed measuring CO₂ and H₂O mole fractions at 10 Hz. Air was sampled 20 cm below the
253 mid-point between the anemometer's transducers (effective measurement height of 2.3 m) at
254 8 l min⁻¹ through a 1.5 m long piece of Dekabon© tubing (OD ¼"). Data was logged by a
255 laptop running an in-house data acquisition software written in LabViewTM and were
256 processed offline. Data capture was 58% with 47% of available data points attributable to the
257 North field. After standard filtering and quality control (Helfter et al. 2015), there remained
258 25% of high quality data (19% daytime and 6% night time data). The IRGA was run with a
259 scrubbing column (1:1 mixture of soda lime and drierite) in front of the reference cell rather
260 than a supply of N₂; exhaustion of the chemicals was the greatest cause of data loss (> 80%).

261

262 *Data analysis*

263 For comparing soil properties before and after the ploughing event, paired t-tests were carried
264 out and results with $p < 0.05$ regarded as significant.

265 In an attempt to separate the effects of fertilisation and ploughing on N₂O flux, we used a
266 simple model which describes the expected response to fertilisation. The N₂O flux was
267 expected to increase to a peak value some time after the date of fertilisation, and show an
268 exponential decline thereafter. We used the lognormal density function to represent this

269 pattern in time. Using data from all fertilisation events, we fitted two parameters, μ and
270 σ . Conventionally, these represent the mean and standard deviation of the log-
271 transformed data. However, in this context, μ represents the time delay between fertilisation
272 and the peak flux occurring, and σ represents a decay rate parameter. By expressing the
273 flux data appropriately, these parameters can be found as the mean and standard deviation of
274 a transformed data set, so numerical optimisation is not required. A scaling coefficient was
275 derived by linear regression of these predictions on the observations. In this way, we found
276 the best fit to the observations, given a lognormal-shape pattern following fertilisation. This
277 procedure was applied only to N_2O fluxes, as there was no similar a priori expectation of a
278 response of CH_4 or CO_2 fluxes to fertilisation.

279

280 We statistically analysed whether N_2O fluxes were related to ploughing using a mixed-effects
281 model (Pinheiro and Bates, 2004). This expressed the N_2O flux in terms of four fixed effects:
282 soil temperature, soil moisture, the predicted response following fertilisation, and whether
283 ploughing had recently taken place or not. We also included two nested random effects,
284 accounting for repeated measurements on individual chambers, which were nested within the
285 two fields. For CH_4 and CO_2 , we could fit a simpler model with the same random effects, but
286 only the three fixed effects of soil temperature, soil moisture, and ploughing. All analyses
287 were performed on log-transformed fluxes, so that the data met normality assumptions. To
288 allow for negative values, an offset of 50 was added to CH_4 fluxes.

289

290 **Results**

291 *Rainfall, Temperature and soil moisture*

292 The rainfall patterns in 2012 and 2014 were similar. Cumulative rainfall over the two months
293 prior to ploughing in 2012 was 118 mm, compared with 136 mm in 2014 (Figure 2c,d). Both

294 ploughing events were followed by a similarly wet period: 100 mm for the month of May
295 2012, and 116 mm during the post-ploughing month in 2014, around twice the long-term
296 mean for May.

297

298 In 2012, the average air and soil temperatures in the two weeks before ploughing and one
299 week after ploughing stayed below 10 °C (Figure 2a, 3a). The air temperature only increased
300 to double figures (15 °C) on the 21 May, and stayed between 12 and 18 °C until the end of
301 the measurement period. There was no significant rainfall the week before and the week after
302 ploughing, but from the 31 May (i.e. almost one month after ploughing) rainfall frequency
303 and amount increased (Figure 2c). Because of these cold, dry conditions, germination was
304 very slow.

305

306 In 2014, the soil temperature was around 5 °C warmer at the time of ploughing, compared
307 with 2012 (Figure 3a). Soil temperature rose fairly steadily from 12 °C to 20 °C over the
308 study period following ploughing. In both years, soil temperature increased after ploughing,
309 and the increase was greater in the ploughed field than in the unploughed field (Figure 3a).
310 Unlike in 2012, there was no rainfall in the week before ploughing and reseeding in 2014
311 (Figure 2d), but frequent rain showers within two weeks of the ploughing event together with
312 the warmer temperatures facilitated fast germination and almost complete canopy closure by
313 the end of this much shorter study period.

314 Volumetric soil moisture (VSM) content in 2012 was larger in the NF than the SF
315 irrespective of the ploughing (Figure 3b). In 2014 the VSM in the NF decreased from 70-90%
316 to <30%. The downward trend was stronger after ploughing. The unploughed SF did not
317 show this trend and even showed a slight increase in VSM in June to a maximum of around
318 60% from averages around 40% previously (Figure 3b).

319

320 *Soil properties*

321 Bulk density, total C and N, and KCl extractable NH_4^+ and NO_3^- for the top 10 cm were
322 measured one week before and one and five weeks after ploughing from both ploughed and
323 non-ploughed fields in both years (Table 2). Both ploughing events significantly increased
324 the soil bulk density of the top 5 cm by 37%, from 0.75 g cm^{-3} to 1.19 g cm^{-3} . The small
325 differences in bulk densities between 2012 and 2014 shown in Table 2 are not significant.
326 Total C/N ratio was lower in 2012 than 2014 for both fields, none of the differences between
327 years and fields were significant. In 2012 and 2014 differences in NH_4^+ and NO_3^-
328 concentrations were not significant for the two fields before ploughing. After ploughing the
329 NH_4^+ and NO_3^- concentrations were larger from the ploughed fields compared to the
330 unploughed field, both 1 and 5 weeks after ploughing. These differences were significant for
331 NH_4^+ on both post-ploughing dates in 2012 ($p < 0.001$), and for NO_3^- 1 week after ploughing in
332 both years ($p < 0.05$). In 2012 SF and NF NH_4^+ and NO_3^- increased with time between pre-
333 ploughing and 1 week later, and also between the 1 week and 5 week measurements.
334 Differences were significant at $p < 0.05$ and above for all, except for NO_3^- concentrations from
335 the SF 1 and 5 weeks after ploughing and the NF pre and 1 week after ploughing. In 2014
336 there was no significant change in NH_4^+ and NO_3^- concentrations from the unploughed SF.

337

338 *N₂O fluxes*

339 Background mean fluxes in early spring in both years were $< 5 \mu\text{g m}^{-2} \text{ h}^{-1} \text{ N}_2\text{O-N}$ (Figure 4a).
340 After fertilisation events, N_2O fluxes generally showed a peak followed by a decline, and the
341 lognormal density function approximates this pattern in the data reasonably well (fitted lines
342 in Figure 4a). After both ploughing events, N_2O fluxes showed a strong deviation from the
343 pattern expected from fertilisation alone, and increased approximately linearly over the

344 following month, up to around $200 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ in 2012, and to $1300 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$
345 in 2014 (red points in Figure 4a). However, soil temperatures also increased over both
346 periods, so we cannot interpret this simply as a response to ploughing. To separate the effects
347 of fertilisation, temperature and soil moisture from that of ploughing, we used the mixed-
348 effects model analysis. This shows a strong indication that N_2O fluxes were higher after
349 ploughing, after accounting for the effect of fertilisation, temperature and soil moisture
350 (Table 3). Because the mixed-effects model is fitted to the log-transformed flux, the
351 interpretation of the coefficients is not as straight-forward as in the normal case. The
352 exponentiated coefficients are interpreted as the proportional change in flux for a unit change
353 in the independent variable. To translate these into more meaningful units, we calculate the
354 absolute effect size as the difference in the fitted mixed model predictions with and without
355 ploughing, at the mean level of all other inputs (Table 4). This predicts that fluxes were
356 higher after ploughing by $14.1 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ in 2012, and $49.9 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ in 2014.
357 By comparison with the average magnitude of fluxes after fertilisation events, we would
358 expect fluxes to be on average $96 \mu\text{g m}^{-2} \text{ h}^{-1}$ higher, if 1% of 70 kg N ha^{-1} were released as
359 N_2O in the 30 days following fertiliser application (although we would expect this to follow
360 the lognormal pattern in time described previously). We thus estimate that ploughing has an
361 effect which is ~14 - 52 % of that of typical N fertilisation.

362

363 *CH₄ fluxes*

364 Both positive and negative CH_4 fluxes were measured in both years. In early spring in both
365 years on both fields, background fluxes ranged from uptake of a few tens of $\mu\text{g CH}_4\text{-C m}^{-2} \text{ h}^{-1}$
366 to positive emission fluxes of a few tens of $\mu\text{g CH}_4\text{-C m}^{-2} \text{ h}^{-1}$. After ploughing in May 2012,
367 fluxes from the SF increased to a few hundreds of $\mu\text{g CH}_4\text{-C m}^{-2} \text{ h}^{-1}$ (Figure 4b, red points)
368 whilst fluxes from the unploughed NF remained in the order of a few tens of $\mu\text{g CH}_4\text{-C m}^{-2} \text{ h}^{-1}$

369 ¹. After ploughing of the NF in 2014, CH₄ fluxes increased to >5000 μg CH₄-C m⁻² h⁻¹.
370 Fluxes also increased from the SF but only to about 500 μg CH₄-C m⁻² h⁻¹. Again, we used
371 the mixed-effects model to separate the effect of ploughing from the effects of temperature
372 and soil moisture (Table 3). This showed a strong effect of temperature, a weak effect of soil
373 moisture, and a variable response to ploughing. Ploughing decreased CH₄ fluxes by 11 μg m⁻²
374 h⁻¹ in 2012, and increased them by 36.5 μg m⁻² h⁻¹ in 2014 (Table 4). In the absence of
375 ploughing, fertilisation in May in 2012 appeared to increase CH₄ fluxes, and to a lesser extent
376 in August 2012, but there was no effect apparent in 2014 (Figure 4b).

377

378 *Ecosystem respiration rates*

379 Although variable, all 4 random locations on the ploughing day on 2012 demonstrated the
380 immediate increase in CO₂ respiration within the first 30 min after the plough passed that
381 particular area (Figure 5). This physical release of CO₂ remained for at least 3 hours, and
382 fluxes then returned to near- background levels after around 80-90 min.

383

384 Ecosystem respiration rates in 2012 were on average around 250 mg CO₂-C m⁻² h⁻¹ in early
385 spring for both fields (Figure 4c). Results from the mixed-model analysis show that
386 ploughing decreased ecosystem respiration quite consistently, as well as showing a strong
387 positive response to temperature (Table 3). The net effect of ploughing was to decrease
388 ecosystem respiration by 71-85 mg CO₂-C m⁻² h⁻¹ (Table 4). An effect of fertilisation separate
389 from that of temperature was not easily discernible.

390

391 *Net ecosystem exchange of CO₂ measured by eddy covariance*

392 There was a greater than usual occurrence of wind from the N-NW in the summer of 2012
393 which resulted in the near 50:50 split of data collected from NF and SF (Figure 1). The 70:30
394 split in favour of winds blowing from the SW observed in 2014 is more typical for the site.

395

396 The two ploughing events in 2012 and 2014 exhibited multiple similarities in terms of NEE
397 (Figure 6). Daytime uptake of CO₂ by the ploughed field ceased after ploughing and fluxes
398 remained positive for approximately 40 days after the event (Figure 6a and c). This is most
399 obvious at ploughing of the NF in 2014 with highest coverage of eddy covariance data
400 (Figure 6c). After ca. 40 days, CO₂ uptake in the ploughed and re-sown field was comparable
401 to the non-ploughed field in each year; however, the variability in daytime NEE in the two
402 fields was large (2-3 times larger in 2014 than in 2012; Figure 6a and c). Night time fluxes of
403 CO₂ were not statistically different between fields in 2012 (Figure 6b) and the temporal
404 variability was consistent with variations in soil temperature (weak positive correlation of
405 fluxes with soil temperature which peaked in both fields ca. 27 days after ploughing; Figure
406 3a). Night time fluxes in the ploughed NF also followed the upward trend in soil temperature
407 observed in 2014 (Figure 6d and Figure 3a). In contrast, night time respiration in the SF was
408 larger than in the ploughed NF, it was more scattered and did not exhibit a clear correlation
409 with soil temperature. Ploughing had a transient effect on CO₂ fluxes at Easter Bush, with a
410 full recovery of the sink strength observed within 1.5 to 2 months after ploughing and re-
411 sowing.

412

413 Daytime and night time CO₂ fluxes measured by EC increased sharply from the day of
414 ploughing in 2014 and peaked 3 days later (Figure 6c and d) which we attribute to the
415 combined effects of the physical removal of the CO₂ sink and the release of CO₂ from
416 upturned soil layers.

417 Ploughing caused a net release of carbon of the order of $120 \text{ g CO}_2\text{-C m}^{-2}$ (95% confidence
418 interval range 87 to $153 \text{ g CO}_2\text{-C m}^{-2}$) during the month following the 2014 ploughing event.
419 Data coverage for the ploughed SF during the month following the 2012 ploughing event was
420 too sparse for the calculation of reliable cumulative fluxes. However, in light of Figure 6 it
421 seems reasonable to assume that the net carbon loss in 2012 would be of similar magnitude as
422 that observed in 2014 under similar meteorological conditions.

423

424 **Discussion**

425 Our results show that ploughing increased N_2O emissions, decreased ecosystem respiration,
426 and had a mixed effect on CH_4 fluxes. We can estimate the total impact of ploughing by
427 adding the increase in N_2O emissions, accounting for their relative global warming potential,
428 to the net release of carbon following ploughing. We assume the net effect on CH_4 is small
429 enough to be negligible. If N_2O emissions are increased by $14\text{-}50 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ over the
430 month following ploughing, converting this to total mass of N_2O and CO_2 equivalent units
431 using a global warming potential of 298 (IPCC 2014), we obtain values of $4\text{-}17 \text{ g CO}_2\text{-eq m}^{-2}$.
432 This is small compared to the $440 \text{ g CO}_2 \text{ m}^{-2}$ released as CO_2 in the month following
433 ploughing, and gives a total of $444 - 457 \text{ g CO}_2\text{-eq m}^{-2}$. To put this into context, this
434 represents 55% of the average harvest yield at this site when managed for hay or silage rather
435 than grazing (Jones et al., submitted). Alternatively, the ploughing loss represents 7% of
436 average GPP at the site. The purpose of ploughing is to increase sward productivity, so GPP
437 would be expected to be larger in subsequent months and years. Whether the ploughing
438 operation is GHG-neutral depends on the magnitude and duration of this longer-term effect
439 on GPP, as this determines when/whether the increased carbon uptake offsets the short-term
440 net source induced by the ploughing operation. This is difficult to discern without a longer
441 term study.

442

443 The ploughing-induced increases in N₂O emissions were rather different in 2012 and 2014, at
444 14 and 50 µg N₂O-N m⁻² h⁻¹, respectively. Because we have accounted for the effects of
445 temperature and soil moisture in the analysis, it is not likely that this is due to differences in
446 weather conditions. The difference between years may be related to different N contents in
447 the vegetation at the time of ploughing. The increase in N₂O emissions following ploughing
448 is most likely due to increases in nitrogen inputs from mineralisation of the organic N in plant
449 litter. In 2014, the ploughing took place six weeks after a fertilisation event, so the N stock in
450 the vegetation was presumably higher than in 2012, when the field had not been fertilised that
451 year. However, the difference in N₂O emission between ploughing events is not clearly
452 reflected in the measured ammonium and nitrate concentrations (Table 2). Similar short lived
453 N₂O emissions after tillage events on managed grassland were measured by other authors
454 (Davies et al. 2001; Velthof et al. 2010; Merbold et al. 2014) and (Ball et al. 1997; Estavillo
455 et al. 2002) linked these to increases in soil NO₃⁻ concentrations, following mineralisation of
456 the organic N in plant litter. An analysis of 39 studies in Europe concluded that incorporation
457 of crop residue into the soil by ploughing resulted in a 6 fold increase in soil respiration rates
458 and 12 fold increase in N₂O emissions (Lethinen et al., 2014). The IPCC default inventory
459 methodology for incorporation of crop residue (De Klein 2013) would predict an N₂O
460 emission of around 50 µg N₂O-N m⁻² h⁻¹ for our site, based on estimates of biomass and plant
461 N content from Jones et al (submitted), a shoot:root ratio of 1.5, using the 1% default
462 emission factor, and assuming this were emitted over a month. This is very close to our
463 higher value, obtained in 2014. The average fertiliser-induced N₂O emission over the 3 weeks
464 after fertilisation for the whole study period ranged from 0.29% to 2.94%.

465

466 Mineral agricultural soils tend to be only small sources and sinks for CH₄, unless irrigated.
467 This is also the case for the Easter Bush fields, for which the average annual CH₄ fluxes were
468 3.4 µg CH₄-C m⁻² h⁻¹ for the period 2007 – 2010 (Skiba et al, 2013). On the ploughed field
469 an additional CH₄ source was the decomposition of the ploughed under grass turf, which
470 provided the labile carbon compounds and anaerobicity required for methanogenesis, and
471 possibly was responsible for the slightly larger CH₄ emissions (Figure 4b). In 2014, CH₄
472 emissions were much larger from the ploughed NF, than the unploughed SF (Figure 4b). It is
473 likely that under these warmer conditions, the main CH₄ source was the decomposition of the
474 grass turf (Yamulki and Jarvis 2002).

475

476 A number of studies reported no conclusive evidence of tillage impacting soil microbial
477 respiration rates in the long term (Yamulki and Jarvis, 2002, Jones et al. 2005, Ball et al,
478 1999). Our observations show a small but consistent decrease in ecosystem respiration rate
479 following ploughing. However, it is important to make the distinction between soil
480 respiration rate and ecosystem respiration rate (ie. including the above-ground plants), as the
481 system definitions are different. When comparing ecosystem respiration rate before and after
482 ploughing, the total biomass is initially the same, except the plants are over-turned, mostly
483 dead and no longer respiring. The ecosystem respiration rate will therefore generally
484 decrease. When comparing soil respiration rate before and after ploughing, the total biomass
485 is generally increased after ploughing, as the above-ground plant material is now
486 incorporated in to the soil. The soil respiration rate will therefore generally decrease. The
487 physical release of CO₂ trapped in soil air for several days immediately after the ploughing of
488 grassland soils (Kessavalou et al. 1998) and arable soils (Reicosky 1997; Vinten et al. 2002,
489 Omonde et al. 2007) only makes a small contribution to the overall CO₂ emissions.

490

491 Our estimated net release of $4.0 \text{ g CO}_2\text{-C m}^{-2} \text{ d}^{-1}$ (95% confidence interval range 2.9 to 5.1 g
492 $\text{CO}_2\text{-C m}^{-2} \text{ d}^{-1}$) following the 2014 ploughing event is consistent with other European studies
493 (e.g. Merbold et al. (2014): $2.8 \text{ g CO}_2\text{-C m}^{-2} \text{ d}^{-1}$ for a restored grassland in Switzerland;
494 Willems et al. (2011): $3.1 \pm 1.2 \text{ g CO}_2\text{-C m}^{-2} \text{ d}^{-1}$ for a grassland in Ireland). In contrast, the
495 unploughed SF had a net flux of $-0.9 \text{ g CO}_2\text{-C m}^{-2} \text{ d}^{-1}$ (95% confidence interval range -2.7 to
496 $0.9 \text{ g CO}_2\text{-C m}^{-2} \text{ d}^{-1}$) for the same 2014 time period.

497

498 The tillage management considerably changed the soil physical and chemical properties, broadly in
499 the same manner on both fields in both years. Both tillage events, increased the bulk density in the top
500 5 cm soil depth from 0.77 g cm^{-3} to 1.22 g cm^{-3} (Table 2). The ploughing induced increase in bulk
501 density is caused by the mechanically disruption of stable soil aggregates and mixing lighter more
502 organic top soil with heavier mineral soil from the deeper layers. After the soil is rolled, the newly
503 arranged soil aggregates are compacted and porosity and conductivity between pores decrease in the
504 upper top soil layer (Ball, 2013). The reduction of soil aggregation increases evaporation (Six et
505 al., 1998) and explains our observed reduction in soil moisture content after ploughing from
506 both fields (Figure 3b). Average volumetric soil moisture content from the ploughed fields in
507 2012 (SF) and 2014 (NF) were 44% and 21% lower than from the unploughed fields.

508

509 Mineralisation rates are also favoured by the physical turnover of soil and break up of
510 aggregates during ploughing by exposing new surfaces to the more oxygen rich atmosphere
511 and by ploughing in the grass turf. Depending on the C/N ratio of the plant material,
512 incorporation can either lead to immobilisation or mineralisation (Davis et al., 2001). At
513 Easter Bush, the C/N ratios in the top 10 cm of the soil did not change significantly over the 6
514 week period, 1 week before to 5 weeks after tillage (Table 2). We observed a 10 and 5 fold
515 increase in top soil (0 -10 cm) NH_4^+ and NO_3^- concentrations in the first 5 weeks after
516 ploughing in 2012 from the ploughed SF, but also a 7 and 5 fold increase in NH_4^+ and NO_3^-

517 concentrations from the unploughed NF. This implies that the raised concentrations are a
518 result of several factors; weather and ploughing on the SF and climate and excreta and urine
519 from the sheep grazed NF. The reason for the much larger NH_4^+ concentrations before
520 ploughing in 2014 compared to 2012 are not obvious. In 2014 ploughing resulted in a
521 significant decrease of NH_4^+ and increase of NO_3^- concentrations, presumably caused by
522 nitrification (Table 2). With hindsight, total C and N and NH_4^+ and NO_3^- concentrations
523 should have been measured for the entire plough depth (30 cm). The mixing of the soil layers
524 and incorporation of the turf to the deeper layers will have created hotspots of
525 mineralisation/immobilisation, which we could not account for by the 0-10 cm soil analysis.

526

527 **Conclusions**

528 Ploughing significantly increased fluxes of N_2O , reduced ecosystem respiration rate, and had
529 a variable effect on CH_4 fluxes. The effect on N_2O is small, but distinguishable from the
530 effects of N fertilisation, soil temperature and soil moisture. Tillage-induced N_2O fluxes were
531 close to expectations based on the IPCC default methodology. By far the dominant effect on
532 the GHG balance was the temporary reduction in GPP.

533

534 **Acknowledgements**

535 The authors would like to thank Wim Bosma, farm manager for the Easter Bush field site, for
536 site access. We are grateful to Nick Cowan, Helen Gordon, Zhaowei Gu, Wei An and Angela
537 Tellez-Rio for assistance with field work. We also thank DEFRA and the Scottish
538 Government for financial support through the UK GHG Platform project AC0116 (The
539 InveN2Ory project).

540 **References**

- 541 Ball B C 2013 Soil structure and greenhouse gas emissions: a synthesis of 20 years of
542 experimentation. *European Journal of Soil Science* 64, 357-373.
- 543 Ball B C, Griffiths B S, Topp C F E, Wheatley R, Walker R L, Rees R M, Watson C A, Gordon H,
544 Hallett P D, McKenzie B M and Nevison I M 2014 Seasonal nitrous oxide emissions
545 from field soils under reduced tillage, compost application or organic farming.
546 *Agriculture, Ecosystems & Environment* 189, 171-180.
- 547 Ball B C, Horgan G W, Clayton H and Parker J P 1997 Spatial Variability of Nitrous Oxide
548 Fluxes and Controlling Soil and Topographic Properties. *J. Environ. Qual.* 26, 1399-
549 1409.
- 550 Ball B C, Scott A and Parker J P 1999 Field N₂O, CO₂ and CH₄ fluxes in relation to tillage,
551 compaction and soil quality in Scotland. *Soil and Tillage Research* 53, 29-39.
- 552 Brady N C and Weil R R 2002 *The Nature and Properties of Soils*, New Jersey: Prentice Hall.
- 553 Campbell B D and Stafford Smith D M 2000 A synthesis of recent global change research on
554 pasture and rangeland production: reduced uncertainties and their management
555 implications. *Agriculture, Ecosystems & Environment* 82, 39-55.
- 556 Clayton H, Arah J R M and Smith K A 1994 Measurement of nitrous oxide emissions from
557 fertilized grassland using closed chambers. *Journal of Geophysical Research:*
558 *Atmospheres* 99, 16599-16607.
- 559 Davies M, Smith K and Vinten A 2001 The mineralisation and fate of nitrogen following
560 ploughing of grass and grass-clover swards. *Biol Fertil Soils* 33, 423-434.
- 561 EEA 2005 *The European Environment. State and Outlook 2005*. Ed. E E Agency.,
562 Copenhagen.
- 563 Eriksen J and Jensen L S 2001 Soil respiration, nitrogen mineralization and uptake in barley
564 following cultivation of grazed grasslands. *Biol Fertil Soils* 33, 139-145.
- 565 Estavillo J M, Merino P, Pinto M, Yamulki S, Gebauer G, Sapek A and Corré W 2002 Short
566 term effect of ploughing a permanent pasture on N₂O production from nitrification
567 and denitrification. *Plant and Soil* 239, 253-265.
- 568 Helfter C, Campbell C, Dinsmore K J, Drewer J, Coyle M, Anderson M, Skiba U, Nemitz E,
569 Billett M F and Sutton M A 2015 Drivers of long-term variability in CO₂ net
570 ecosystem exchange in a temperate peatland. *Biogeosciences* 12, 1799-1811.
- 571 IPCC 2014 Summary for Policymakers. In *Mitigation of Climate Change. Contribution of*
572 *Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on*
573 *Climate Change.*, Cambridge, United Kingdom and New York, NY, USA.
- 574 Jones S K, Rees R M, Skiba U M and Ball B C 2005 Greenhouse gas emissions from a
575 managed grassland. *Global and Planetary Change* 47, 201-211.
- 576 Jones S, Helfter C, Anderson M, Coyle M, Campbell C, Famulari D, Di Marco C, van Dijk N,
577 Topp K, Kiese R, Kindler R, Siemens J, Schruppf M, Kaiser K, Nemitz E, Levy P, Rees R,
578 Sutton M, and Skiba U 2016 The nitrogen, carbon and greenhouse gas budget of a
579 grazed, cut and fertilised temperate grassland, *Biogeosciences Discussions*, bg-2016,
580 submitted
- 581 Karlen D L, Kovar J L, Cambardella C A and Colvin T S 2013 Thirty-year tillage effects on crop
582 yield and soil fertility indicators. *Soil & Tillage Research* 130, 24-41.
- 583 Kessavalou A, Mosier A R, Doran J W, Drijber R A, Lyon D J and Heinemeyer O 1998 Fluxes of
584 Carbon Dioxide, Nitrous Oxide, and Methane in Grass Sod and Winter Wheat-Fallow
585 Tillage Management. *J. Environ. Qual.* 27, 1094-1104.

586 Kormann R and Meixner F X 2001 An analytical footprint model for non-neutral
587 stratification. *Boundary-Layer Meteorology* 99, 207-224.

588 Lehtinen T, Schlatter N, Baumgarten A, Bechini L, Krüger J, Grignani C, Zavattaro L,
589 Costamagna C and Spiegel H 2014 Effect of crop residue incorporation on soil organic
590 carbon and greenhouse gas emissions in European agricultural soils. *Soil Use and*
591 *Management* 30, 524-538.

592 Levy P E, Burden A, Cooper M D A, Dinsmore K J, Drewer J, Evans C, Fowler D, Gaiawyn J,
593 Gray A, Jones S K, Jones T, McNamara N P, Mills R, Ostle N, Sheppard L J, Skiba U,
594 Sowerby A, Ward S E and Zielinski P 2012 Methane emissions from soils: synthesis
595 and analysis of a large UK data set. *Global Change Biology* 18, 1657-1669.

596 MacDonald J D, Rochette P, Chantigny M H, Angers D A, Royer I and Gasser M-O 2011
597 Ploughing a poorly drained grassland reduced N₂O emissions compared to chemical
598 fallow. *Soil and Tillage Research* 111, 123-132.

599 Merbold L, Eugster W, Stieger J, Zahniser M, Nelson D and Buchmann N 2014 Greenhouse
600 gas budget (CO₂, CH₄ and N₂O) of intensively managed grassland following
601 restoration. *Global Change Biology* 20, 1913-1928.

602 Omonode R A, Vyn T J, Smith D R, Hegyemegi P and Gál A 2007 Soil carbon dioxide and
603 methane fluxes from long-term tillage systems in continuous corn and corn-soybean
604 rotations. *Soil and Tillage Research* 95, 182-195.

605 Pagliai M, Vignozzi N and Pellegrini S 2004 Soil structure and the effect of management
606 practices. *Soil & Tillage Research* 79, 131-143.

607 Pinheiro JC, Bates DM 2004 *Mixed-effects models in S and S-PLUS*. New York: Springer.

608 Reicosky D C 1997 Tillage-induced CO₂ emission from soil. *Nutrient Cycling in*
609 *Agroecosystems* 49, 273-285.

610 Six J, Elliott E T and Paustian K 2000 Soil macroaggregate turnover and microaggregate
611 formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology*
612 *and Biochemistry* 32, 2099-2103.

613 Skiba U, Jones S K, Dragosits U, Drewer J, Fowler D, Rees R M, Pappa V A, Cardenas L,
614 Chadwick D, Yamulki S and Manning A J 2012 UK emissions of the greenhouse gas
615 nitrous oxide. *Philosophical Transactions of the Royal Society B-Biological Sciences*
616 367, 1175-1185.

617 Skiba U, Jones S K, Drewer J, Helfter C, Anderson M, Dinsmore K, McKenzie R, Nemitz E and
618 Sutton M A 2013 Comparison of soil greenhouse gas fluxes from extensive and
619 intensive grazing in a temperate maritime climate. *Biogeosciences* 10, 1231-1241.

620 Soane B D, Ball B C, Arvidsson J, Basch G, Moreno F and Roger-Estrade J 2012 No-till in
621 northern, western and south-western Europe: A review of problems and
622 opportunities for crop production and the environment. *Soil and Tillage Research*
623 118, 66-87.

624 Soussana J F, Allard V, Pilegaard K, Ambus P, Amman C, Campbell C, Ceschia E, Clifton-Brown
625 J, Czobel S, Domingues R, Flechard C, Fuhrer J, Hensen A, Horvath L, Jones M, Kasper
626 G, Martin C, Nagy Z, Neftel A, Raschi A, Baronti S, Rees R M, Skiba U, Stefani P,
627 Manca G, Sutton M, Tuba Z and Valentini R 2007 Full accounting of the greenhouse
628 gas (CO₂, N₂O, CH₄) budget of nine European grassland sites. *Agriculture,*
629 *Ecosystems & Environment* 121, 121-134.

630 Uchida Y, Clough T J, Kelliher F M and Sherlock R R 2008 Effects of aggregate size, soil
631 compaction, and bovine urine on N₂O emissions from a pasture soil. *Soil Biology and*
632 *Biochemistry* 40, 924-931.

633 Velthof G L, Hoving I E, Dolfing J, Smit A, Kuikman P J and Oenema O 2010 Method and
634 timing of grassland renovation affects herbage yield, nitrate leaching, and nitrous
635 oxide emission in intensively managed grasslands. *Nutrient Cycling in*
636 *Agroecosystems* 86, 401-412.

637 Vinten A J A, Ball B C, O'Sullivan M F and Henshall L J K 2002 The effects of cultivation
638 method, fertilizer input and previous sward type on organic C and N storage and
639 gaseous losses under spring and winter barley following long-term leys. *The Journal*
640 *of Agricultural Science* 139, 231-243.

641 Willems, A. B., C. A. Augustenborg, et al. 2011 Carbon dioxide emissions from spring
642 ploughing of grassland in Ireland. *Agriculture Ecosystems & Environment* 144(1),
643 347-351.

644 Yamulki S and Jarvis S 2002 Short-term effects of tillage and compaction on nitrous oxide,
645 nitric oxide, nitrogen dioxide, methane and carbon dioxide fluxes from grassland.
646 *Biol Fertil Soils* 36, 224-231.

647

648

649

650 **Figure Captions**

651 Figure 1: Satellite image (Google Earth; imagery date July 2012) showing the outline of the
652 South field (SF) and the North field (NF), and the locations of the three eddy-covariance
653 systems used during the two ploughing events of 2012 and 2014. The long-term, fixed eddy-
654 covariance system (“EC fenceline”) is located along the fence which separates the two fields.
655 A temporary eddy-covariance system was deployed in the SF (“EC (May – August 2012)”)
656 during the spring and summer of 2012 to monitor pre- and post-ploughing fluxes within the
657 ploughed field. A different system (see materials and methods section for details) was
658 deployed in the NF (“EC (May-August 2014)”) during the spring and summer of 2014.
659 Overlain onto the satellite image are median values of x_{\max} (red line), x_{50} (green line) and x_{70}
660 (purple line) (distance in meters from the EC mast where peak, 50% and 70% of the
661 measured fluxes originated, respectively) for spring and summer 2012 as in this instance
662 fluxes from the same tower could come from either field and plotted per 10 deg wind
663 direction bins. These footprint statistics were obtained with the analytical Kormann-Meixner
664 footprint model for non-neutral stratification (Kormann and Meixner, 2001).

665
666 Figure 2: Average daily air temperature ($^{\circ}\text{C}$) (a, b) and daily rainfall (mm) (c, d) in 2012 (left,
667 a & c) and 2014 (right, b & d). Ploughing was on the 1st May in 2012 and the 20th May in
668 2014 indicated by the dashed vertical red line.

669
670 Figure 3: a) Soil Temperature ($^{\circ}\text{C}$) and b) Volumetric Soil Moisture (%) in 2012 (left panel)
671 and 2014 (right panel) for North Field (NF) and South Field (SF), respectively.
672 Measurements after ploughing in red and unploughed in blue. Fertilisation events indicated
673 by blue horizontal line and ploughing by red horizontal line. To aid visualisation a smooth
674 line was fitted through the data points.

675

676 Figure 4: Log fluxes of N₂O (a), CH₄ (b) [$\mu\text{g m}^{-2} \text{h}^{-1}$] and CO₂ (c) [$\text{mg m}^{-2} \text{h}^{-1}$] in 2012 (left
677 panel) and 2014 (right panel) for North Field (NF) and South Field (SF), respectively.
678 Measurements after ploughing in red and unploughed in blue. Fertilisation events indicated
679 by blue horizontal line and ploughing by red horizontal line. A simple exponential decay after
680 fertilisation fitted as blue line through log N₂O fluxes to indicate fertilisation induced
681 predicted flux.

682

683 Figure 5: Soil CO₂ respiration rates on the day of ploughing. The bars represent average
684 values from 4 measurement positions, the error bars are standard deviation. Time is the
685 period in minutes after the plough passed the 4 plots on 5 repeated occasions.

686

687 Figure 6: Day time and night time fluxes of carbon dioxide (CO₂) measured by an eddy-
688 covariance system installed along the fence line separating the north field (NF) and the south
689 field (SF); (a)-(b) 2012 fluxes and (c)-(d) 2014 fluxes.

690

691