Appendix 8 of BD5104
GHG emissions and modelling

The purpose of this Appendix is to further describe the methods and findings relating to the measurement of greenhouse gas (GHG) fluxes, specifically of methane (CH_4) and nitrous oxide (N_2O) fluxes, which are summarised in Section 4.2.15 of the main body of the report. The methods summaries, results and discussions are not repeated here but instead the full details of the methods are given. Additionally, N_2O fluxes for each management in each year are also shown.

Methods

Each permanent plot on each site had a circular area chosen and marked for GHG (CH_4 and N_2O) flux measurements. A 20 cm diameter circle with no vascular plants was marked by removing the moss layer from the surface to create a bare peat measurement area. During 2012 – 2013, fluxes were measured using cover boxes (a modification on the static chamber method described in Livingston & Hutchinson, 1995) over these vegetation free plots. Dense overhanging vascular plants were clipped back to allow access. During field visits, any plants growing within these circles were removed prior to measurements. From June 2014 onwards, N_2O measurements were discontinued (see below; as fluxes were very small without any significant differences between managements) and CH_4 fluxes were measured in real time using an Ultraportable Greenhouse Gas Analyser (UGGA; Model 915-0011, Los Gatos Research, Inc., San Jose, CA, USA). From June 2015, CH_4 fluxes were also measured on the re-growing (vegetated) plots which were used for the net ecosystem exchange measurements. Although these included only the re-growing vegetation (i.e. heather was clipped in 2013 for biomass assessment), these CH_4 measurements still included vegetation typical for each plot but without any of the previously tall heather. The GHG fluxes at a single site were always measured on the same day as each other and as the NEE and SR fluxes in order to reduce climate variations between plots in a single measurement set. For measurement dates see Appendix 6 (**Table A6.1**).

Cover-box measurements

The cover-boxes comprised a 10 cm tall collar and 15 cm tall chamber, both of which were 20 cm in diameter and made of uPVC pipe (Plumb Center, Wolseley UK Ltd, Leamington Spa, UK). The chambers were topped with circular pieces of uPVC which were glued in place. The chambers were insulated with reflective wadding to minimise any internal temperature change (internal chamber temperatures were monitored periodically and, even on hot days, changed by less than 3°C during the whole closure period). The end of a 2 m length of vacuum tubing (Tygon Formulation R-3603 Tubing, Part number AAC00002, Saint-Gobain Performance Plastics, Akron, OH, USA) was pushed through a rubber bung (SubaSeal No. 25, Sigma-Aldrich, St Louis, MO, USA) which was secured in a small hole drilled through the top of each chamber. The non-chamber end of the tubing was knotted to create a closed system when the chamber and collar were sealed together.

All plots in a pair of blocks were measured simultaneously. Collars were inserted into the indents created in the CH_4 patches by moss removal. Chambers were placed on top and sealed by means of a 10 cm wide rubber band rolled over the join. Wet *Sphagnum* moss was packed around the base of the collars to create an airtight seal (i.e. no collars were inserted into the peat as to prevent any damage to roots and altered decomposition fluxes). Gas samples were extracted 5, 15, 25 and 50 minutes after the chambers were

sealed by inserting the hypodermic needle (Microlance 0.5 mm x 25 mm, Becton Dickinson & Company Limited, Drogheda, Ireland) of a 20 ml syringe into the tubing above the knot, flushing the syringe three times to equilibrate the gas in the tubing with that in the chamber and injecting the sample into a pre-evacuated 12 ml vial (Exetainer 839W, Labco Ltd, High Wycombe, UK).

The gas samples were stored at ambient temperature and analysed within one month. Gas chromatography flame ionisation detection (GC-FID; AutoSystem XL Gas Chromatograph (GC), Perkin Elmer Arnel, Waltham, MA, USA) was used to quantify CH_4 and N_2O concentrations in each vial, aided by a 60-space custom built carousel (Biology Mechanical Workshop, University of York, UK). Blanks (pure nitrogen), standards (a reference gas containing 10 ppm N_2O, 100 ppm CH_4, BOC Gases, Guildford, UK) and air (ambient air) samples were used to calibrate results.

Ultraportable greenhouse gas analyser (UGGA) measurements

The UGGA (Los Gatos, USA) was connected to a modified (a pressure vent was added in the chamber top) cover box chamber with two sections of tubing (Bev-a-line IV, Thermoplastic Processes, Inc., Georgetown, DE, USA), including a 25 ml water trap and an air filter, creating a closed system. The chamber was placed gently onto the CH_4 circle of a plot and sealed around with wet *Sphagnum* to obtain an airtight seal. A tablet (Google Nexus, Google Inc., Mountain View, CA, USA) was used to view the flux in real time. On plots where fluxes spiked and then dropped suddenly, the chamber was removed, vented and replaced as these measurements indicated release of a CH_4 bubble, probably caused by chamber placement disturbance, not a true flux. Fluxes were generally measured over a maximum of 3-5 minutes.

Data processing

For all fluxes, the obtained gas concentrations (ppm) were corrected for temperature differences (measured automatically by the analysers or manually inside the chambers) based on the ideal gas law. Fluxes were then estimated based on the slope of gas concentration change over time. For the GC CH_4 and N_2O measurements taken using cover boxes, fluxes were derived by regressing the five concentrations of each gas against the time points the samples were withdrawn from the chambers and the change in CH_4 or N_2O was calculated. Similarly, for measurements using the UGGA, CH_4 fluxes were derived by regressing the most linear 90 s section of the measurements over time and calculating the increase in CH_4. With all sets of measurements, the flux was discarded and recorded as zero if the R^2 value of the linear slope was less than 0.5 for CH_4 and less than 0.8 for N_2O. Whilst the set R^2 threshold value for CH_4 is low, this reflected some very low CH_4 fluxes at colder temperatures with measurement variability being generally large. All fluxes were also assessed by eye to verify the robustness of the section of the linear trend (i.e. reflecting slightly different flux stabilisation times after chamber placement). The chamber volume (including tubing, water trap and air filter) and collar surface area were used to adjust all fluxes for the effective chamber volume so they could be expressed in nmol m^{-2} s^{-1}. A flux comparison between the two approaches (i.e. cover box versus UGGA) is shown in **Figure A8.1**.

Moreover, for each vegetated plot location (i.e. for UGGA fluxes only) the vegetation composition was recorded as a percentage of heather, sedge (*Eriophorum* spp.), *Sphagnum* and/or other moss. The assessment was done in the field and was also verified by comparing it to photographs taken each year. This information, particularly the percentage sedge cover, was used in the methane flux data analysis (see below).

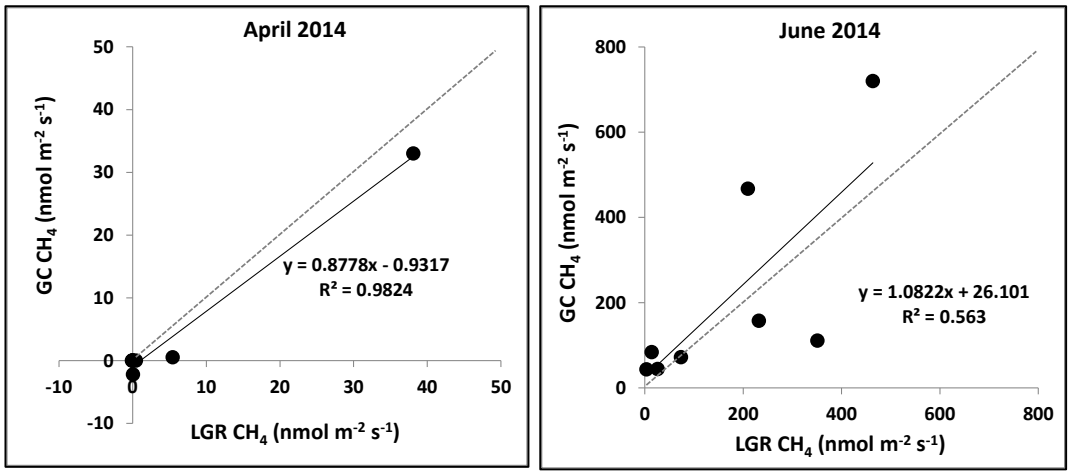

Figure A8.1 Comparison in 2014 of manual chamber CH_4 (methane) fluxes (four GC samples during 50 min closure) versus continuous chamber fluxes (every 2 seconds over 2-3 minutes) using the Los Gatos LGR analyser: (left; low fluxes) Nidderdale in April for mown (with brash left) and uncut plots and (right; high fluxes) Mossdale in June for mown (with brash removed) and uncut plots.

Data analysis

All statistical analyses were carried out in R version 3.3.1 (R Core Team, 2016). Following Zuur et al. (2009), residuals were plotted against fitted values and visually assessed for normality and homogeneity of variance. The critical p-value chosen for significance was 0.05. For a statistical output summary table of the methane fluxes see **Table A6.4** in Appendix 6.

Linear mixed effects models employing the "lmer" function from the "lmerTest" package (Kuznetsova et al., 2016) were used to test for management and site effects on CH_4 and N_2O fluxes. Due to producing many small fluxes (i.e. close to 0) and very few large fluxes, fluxes were square-root transformed for analysis. Additionally, fluxes over 2000 nmol CH_4 m^{-2} s^{-1} were removed before analysis as these likely indicated bubbles which were not detected in the field. The managements, sites and time period (either pre-management, i.e. before management implementation, or post-management, i.e. after management implementation) were used as fixed effects, as were the interactions between them. The month in which measurements were made was also included as a fixed effect as were appropriate environmental variables; soil temperature (Tsoil) and the average WTD in the four weeks before CH_4 measurements (WTD_4wk) were included in the CH_4 model and Tsoil and WTD on the day of flux measurement in the N_2O model. A random intercept was included for each model, with a nested structure of blocks in sites (to account for spatial heterogeneity) in years (to account for repeated measurements). Following the 10-step protocol in section 5.10 of Zuur et al. (2009), variables were dropped stepwise from each linear mixed effects model and the log-likelihood ratio and AIC value were used to assess whether a variable should be dropped or kept in the model. For the final models, the "Satterthwaite" option was used to calculate the denominator degrees of freedom as the time periods resulted in an unbalanced design (Spilke et al., 2005). Where significant interactions were found, the "glht" function with the "Tukey" option from the "multcomp" package (Hothorn et al., 2008) was used to compare groups within the interaction terms.

The CH_4 fluxes were also split (into three groups) by measurement method into GC-FID-analysed data, UGGA data on bare peat and UGGA data on vegetated ground and were analysed separately as CH_4 fluxes generally increased with higher vegetation cover (see **Figure A8.2**), particularly including sedges. Although linear mixed models were used by the method specified above, the random effects were dropped from all

the models meaning that the final analyses were conducted using ANOVAs (function "aov", coupled with the function "Anova" from the "car" package to obtain Type II ANOVA tables; Fox and Weisberg, 2011). Management and site were used as fixed effects for all three groups (i.e. measurement method) but time period was only included for the cover-box data as the other two datasets began after the pre-management period ended. The month of measurement, Tsoil and WTD_4wk were also included as fixed effects in all models and the percentage cover of sedge within each vegetated collar area was included in the model using the UGGA data from vegetated ground.

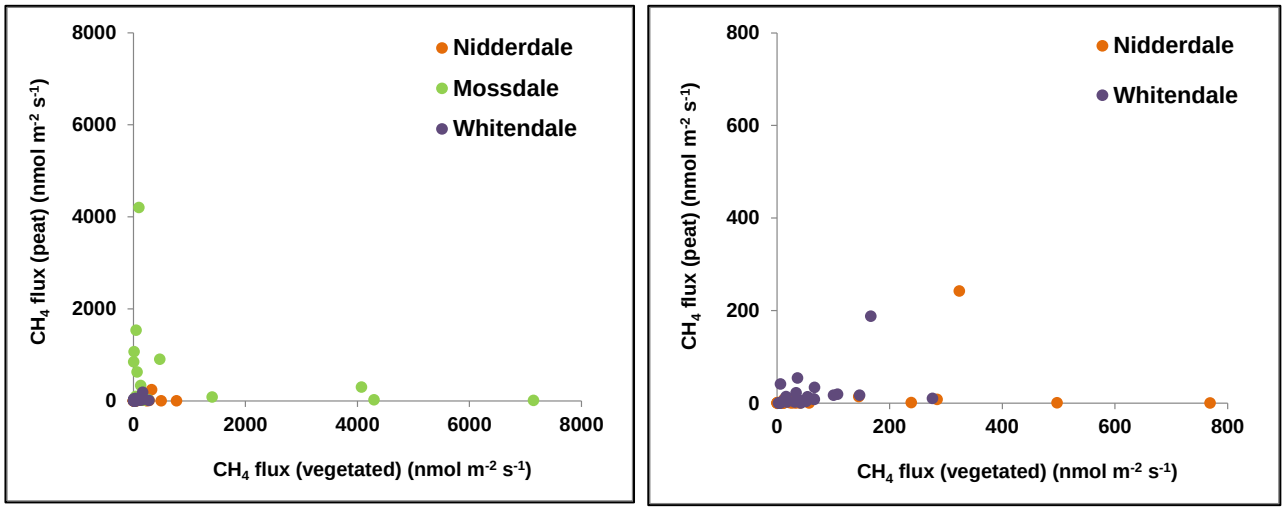

Figure A8.2 Comparison of CH_4 (methane) fluxes (in nmol m^{-2} s^{-1}) using the Los Gatos UGGA analyser on uncut plots on either vegetation free (bare peat) or vegetated areas (regrown since heather cutting in 2013) for all three sites (**left**) or for only Nidderdale and Whitendale (**right**); the overall plant mediated transfer (vegetated - peat) was 62%).

Upscaling CH_4 fluxes

The CH_4 fluxes were up-scaled to annual fluxes for the main managements (uncut, FI, LB) and also the individual managements (i.e. including brash removal and *Sphagnum* additions). CH_4 fluxes were up-scaled using time only as they showed only weak relationships with environmental variables. Each CH_4 flux was converted from nmol CH_4 m^{-2} y^{-1} to g C m^{-2} y^{-1} using the molecular weight of CH_4. Fluxes were then averaged across managements and sites within years.

Whilst the combined (i.e. for the ± *Sphagnum* pellet addition) CH_4 fluxes are shown in the main report (i.e. no significant differences between the treatments), the below **Table A8.1** provides the mean fluxes (including 10 very high emission fluxes, one at Whitendale and 9 at Mossdale) individually for ±*Sphagnum* pellet additions for the two mown treatments (with or without brash removal).

Table A8.1 Mean annual CH_4 fluxes (g C m^{-2} yr^{-1}; mean ± 1 SE) based on manual chamber fluxes taken 3-4 times per year during the pre- (2012) and post-management (2013-2016) period with the values for mown plots with and without *Sphagnum* addition shown separately. Whilst in 2012-2014 only fluxes from non-vegetated areas were available, in 2015 and 2016 CH_4 fluxes were measured from the re-vegetating plots from the same areas that the NEE fluxes were measured. Note: shown averages include the high methane emissions above 2000 nmol CH_4 m^{-2} s^{-1}.

Nidderdale	2012 Pre-management	2013 Post-management	2014	2015	2016	2013-2016 Post-management combined
Code **Treatment**						
T1 Mown, brash left, -Sphagnum	0.7 ± 1.0	2.3 ± 2.6	73.9 ± 37.1	8.8 ± 2.9	39.2 ± 30.9	31.1 ± 9.2
T4 Mown, brash left, +Sphagnum	2.5 ± 2.4	0.0 ± 0.1	24.5 ± 19.4	13.2 ± 7.4	18.4 ± 8.6	14.0 ± 4.4
T5 Mown, brash removed, -Sphagnum	3.2 ± 1.8	1.8 ± 1.7	5.3 ± 2.6	20.9 ± 10.7	4.0 ± 2.4	8.0 ± 2.2
T3 Mown, brash removed, +Sphagnum	0.2 ± 0.1	1.3 ± 0.5	7.8 ± 6.0	9.1 ± 4.0	5.4 ± 1.4	5.9 ± 1.5

Mossdale	2012 Pre-management	2013 Post-management	2014	2015	2016	2013-2016 Post-management combined
Code **Treatment**						
T1 Mown, brash left, -Sphagnum	1.7 ± 0.8	0.3 ± 0.5	8.4 ± 4.0	44.6 ± 17.8	15.4 ± 4.7	17.2 ± 3.4
T4 Mown, brash left, +Sphagnum	4.6 ± 2.3	2.9 ± 2.0	22.7 ± 13.2	6.5 ± 3.4	11.8 ± 4.1	11.0 ± 2.8
T5 Mown, brash removed, -Sphagnum	3.6 ± 2.9	3.2 ± 2.9	47.7 ± 27.2	230.2 ± 86.7	214.7 ± 155.0	124.0 ± 34.0
T3 Mown, brash removed, +Sphagnum	24.3 ± 9.6	0.7 ± 4.1	83.4 ± 42.7	38.4 ± 15.9	24.8 ± 10.2	36.8 ± 9.1

Whitendale	2012 Pre-management	2013 Post-management	2014	2015	2016	2013-2016 Post-management combined
Code **Treatment**						
T1 Mown, brash left, -Sphagnum	-0.2 ± 0.1	0.3 ± 0.2	1.9 ± 0.7	11.9 ± 4.8	13.3 ± 6.6	6.8 ± 1.5
T4 Mown, brash left, +Sphagnum	0.1 ± 0.2	1.5 ± 0.6	26.3 ± 14.6	22.7 ± 6.2	14.2 ± 4.1	16.2 ± 3.2
T5 Mown, brash removed, -Sphagnum	1.2 ± 0.6	0.2 ± 0.5	28.3 ± 13.7	36.9 ± 17.7	45.1 ± 29.6	27.6 ± 7.7
T3 Mown, brash removed, +Sphagnum	6.3 ± 6.0	1.0 ± 0.6	8.1 ± 4.0	25.1 ± 7.8	20.2 ± 5.7	13.6 ± 2.3

Whilst the combined CH_4 fluxes shown in **Table 16** in the main report and in **Table A8.1** above included all methane fluxes, the below **Table A8.2** and **Table A8.3** provide the corresponding average fluxes excluding the 10 very high fluxes above 2000 nmol CH_4 m^{-2} s^{-1} (1 at Whitendale and 9 at Mossdale).

Table A8.2 Up-scaled mean annual CH_4 fluxes (g C m^{-2} yr^{-1}; mean ± 1 SE) based on manual chamber fluxes taken 3-4 times per year during the pre- (2012) and post-management (2013-2016) period with the values combined for mown plots with and without *Sphagnum* addition. Whilst in 2012-2014 only fluxes from non-vegetated areas were available, in 2015 and 2016 CH_4 fluxes were measured from the re-vegetating plots from the same areas that the NEE fluxes were measured. Data exclude 10 fluxes out of 1368 (1 at Whitendale and 9 at Mossdale), which had values over 2000 nmol CH_4 m^{-2} s^{-1}.

Nidderdale		2012 Pre-management	2013 Post-management	2014	2015	2016	2013-2016 Post-management combined
Code	**Treatment**						
FI	Control (Burnt)	3.1 ± 2.3	0.2 ± 0.1	1.6 ± 0.6	2.3 ± 0.7	9.4 ± 4.8	3.4 ± 0.8
DN	Do nothing (uncut)	0.1 ± 0.1	1.1 ± 0.8	4.0 ± 3.4	4.4 ± 1.6	73.7 ± 26.6	20.8 ± 4.1
BR	Mown, brash removed	1.7 ± 0.9	1.6 ± 0.8	6.5 ± 3.2	15.0 ± 5.7	4.7 ± 1.4	7.0 ± 1.4
LB	Mown, brash left	1.6 ± 1.3	1.2 ± 1.3	49.2 ± 21.1	11.0 ± 3.9	28.8 ± 15.8	22.5 ± 5.3

Mossdale		2012 Pre-management	2013 Post-management	2014	2015	2016	2013-2016 Post-management combined
Code	**Treatment**						
FI	Control (Burnt)	5.4 ± 3.1	3.7 ± 1.2	9.4 ± 3.0	12.6 ± 4.4	12.1 ± 3.8	9.4 ± 1.6
DN	Do nothing (uncut)	15.7 ± 8.1	6.6 ± 3.1	36.7 ± 12.6	72.9 ± 34.0	11.6 ± 2.8	31.9 ± 6.6
BR	Mown, brash removed	13.9 ± 5.3	2.0 ± 2.5	65.5 ± 25.1	93.2 ± 22.5	45.4 ± 25.9	51.5 ± 9.5
LB	Mown, brash left	3.1 ± 1.2	1.6 ± 1.0	15.5 ± 6.9	25.6 ± 9.6	13.6 ± 3.1	14.1 ± 2.6

Whitendale		2012 Pre-management	2013 Post-management	2014	2015	2016	2013-2016 Post-management combined
Code	**Treatment**						
FI	Control (Burnt)	0.3 ± 0.2	0.1 ± 0.1	0.9 ± 0.4	25.8 ± 19.1	3.2 ± 0.8	7.5 ± 2.6
DN	Do nothing (uncut)	3.7 ± 2.1	1.2 ± 0.4	2.4 ± 0.8	17.3 ± 4.9	21.3 ± 8.4	10.6 ± 1.8
BR	Mown, brash removed	3.7 ± 3.0	0.6 ± 0.4	18.2 ± 7.2	31.0 ± 9.6	32.7 ± 15.0	20.6 ± 4.0
LB	Mown, brash left	-0.1 ± 0.1	0.9 ± 0.3	14.1 ± 7.5	17.3 ± 4.0	13.7 ± 3.8	11.5 ± 1.9

Table A8.3 Mean annual CH_4 fluxes (g C m^{-2} yr^{-1}; mean ± 1 SE) based on manual chamber fluxes taken 3-4 times per year during the pre- (2012) and post-management (2013-2016) period with the values for mown plots with and without *Sphagnum* addition shown separately. Whilst in 2012-2014 only fluxes from non-vegetated areas were available, in 2015 and 2016 CH_4 fluxes were measured from the re-vegetating plots from the same areas that the NEE fluxes were measured. Note: shown averages exclude 10 fluxes out of 1368 (1 at Whitendale and 9 at Mossdale), which had values over 2000 nmol CH_4 m^{-2} s^{-1}.

Nidderdale	2012 Pre-management	2013 Post-management	2014	2015	2016	2013-2016 Post-management combined
Code **Treatment**						
T1 Mown, brash left, -Sphagnum	0.7 ± 1.0	2.3 ± 2.6	73.9 ± 37.1	8.8 ± 2.9	39.2 ± 30.9	31.1 ± 9.2
T4 Mown, brash left, +Sphagnum	2.5 ± 2.4	0.0 ± 0.1	24.5 ± 19.4	13.2 ± 7.4	18.4 ± 8.6	14.0 ± 4.4
T5 Mown, brash removed, -Sphagnum	3.2 ± 1.8	1.8 ± 1.7	5.3 ± 2.6	20.9 ± 10.7	4.0 ± 2.4	8.0 ± 2.2
T3 Mown, brash removed, +Sphagnum	0.2 ± 0.1	1.3 ± 0.5	7.8 ± 6.0	9.1 ± 4.0	5.4 ± 1.4	5.9 ± 1.5

Mossdale	2012 Pre-management	2013 Post-management	2014	2015	2016	2013-2016 Post-management combined
Code **Treatment**						
T1 Mown, brash left, -Sphagnum	1.7 ± 0.8	0.3 ± 0.5	8.4 ± 4.0	44.6 ± 17.8	15.4 ± 4.7	17.2 ± 3.4
T4 Mown, brash left, +Sphagnum	4.6 ± 2.3	2.9 ± 2.0	22.7 ± 13.2	6.5 ± 3.4	11.8 ± 4.1	11.0 ± 2.8
T5 Mown, brash removed, -Sphagnum	3.6 ± 2.9	3.2 ± 2.9	47.7 ± 27.2	151.7 ± 38.1	68.0 ± 52.4	67.7 ± 15.1
T3 Mown, brash removed, +Sphagnum	24.3 ± 9.6	0.7 ± 4.1	83.4 ± 42.7	38.4 ± 15.9	24.8 ± 10.2	36.8 ± 9.1

Whitendale	2012 Pre-management	2013 Post-management	2014	2015	2016	2013-2016 Post-management combined
Code **Treatment**						
T1 Mown, brash left, -Sphagnum	-0.2 ± 0.1	0.3 ± 0.2	1.9 ± 0.7	11.9 ± 4.8	13.3 ± 6.6	6.8 ± 1.5
T4 Mown, brash left, +Sphagnum	0.1 ± 0.2	1.5 ± 0.6	26.3 ± 14.6	22.7 ± 6.2	14.2 ± 4.1	16.2 ± 3.2
T5 Mown, brash removed, -Sphagnum	1.2 ± 0.6	0.2 ± 0.5	28.3 ± 13.7	36.9 ± 17.7	45.1 ± 29.6	27.6 ± 7.7
T3 Mown, brash removed, +Sphagnum	6.3 ± 6.0	1.0 ± 0.6	8.1 ± 4.0	25.1 ± 7.8	20.2 ± 5.7	13.6 ± 2.3

N_2O fluxes flux results

The N_2O fluxes were consistently very low and often near the detection limit, ranging from -0.42 to 1.12 nmol N_2O m^{-2} s^{-1}. The mean flux was 0.03 nmol N_2O m^{-2} s^{-1}, although 86% of the fluxes were 0.00 nmol N_2O m^{-2} s^{-1} meaning that the median flux was 0.00 nmol N_2O m^{-2} s^{-1} and the mean flux excluding zero values was 0.18 nmol N_2O m^{-2} s^{-1}. There was no significant interaction between management and time period ($F_{5, 556}$ = 0.58, p = 0.71; **Figure A8.3**). The N_2O fluxes were not significantly affected by WTD ($F_{1, 137}$ = 0.09, p = 0.76), nor was there a significant effect of Tsoil ($F_{1, 250}$ = 2.46, p = 0.12) and no seasonal effects were observed. Therefore, for further analysis an average flux of 0.035 g N_2O m^{-2} yr^{-1} was applied across all sites and managements.

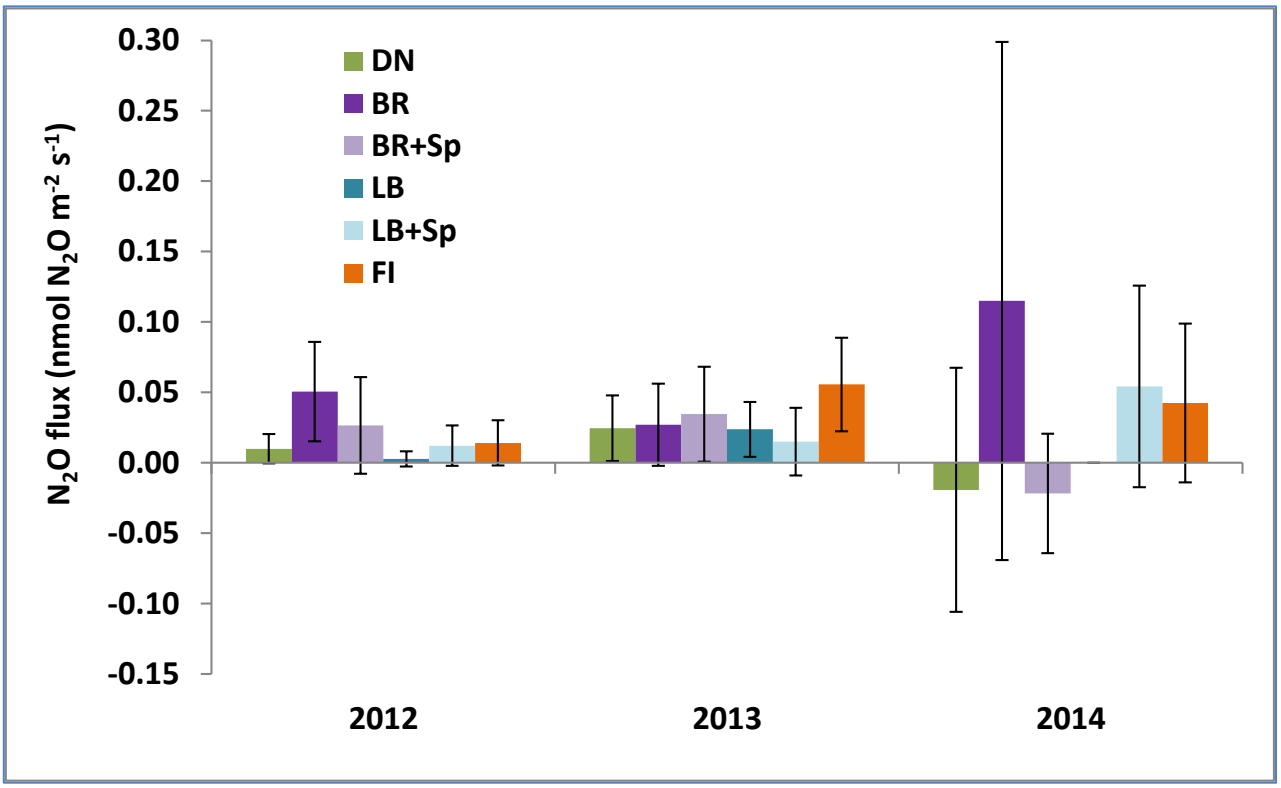

Figure A8.3 Means (± 95% confidence intervals) of N_2O fluxes of each management for the three years for which fluxes were measured (2012 was pre- and 2013 and 2014 were post-management). Management codes were DN (uncut), FI (burnt), BR (mown with brash removed), LB (mown with brash left) and +Sp (*Sphagnum* propagules added).

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