Net ecosystem exchange from two formerly afforested peatlands undergoing restoration in the Flow Country of northern Scotland

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SUMMARY

Northern peatlands are important in the global carbon (C) cycle as they help regulate local, regional and global C budgets through high atmospheric carbon dioxide (CO_2) uptake and low net CO_2 losses to the atmosphere. Since the 1900s (but particularly the 1950s) land-use change has affected many peatland areas, driven in part by attempts to improve their commercial value. During this period, many peatlands in the UK were drained and planted with non-native conifer plantations. Efforts are now underway to restore the ecosystem functioning of these peatlands to those characteristic of pristine peatlands, in particular C flux dynamics. A lack of ecosystem level measurements means that the timescales of restoration and the degree to which they are successful remains poorly determined. In this research, we present the first year-round study of net ecosystem CO_2 exchange (NEE) from peatlands undergoing restoration from forestry. Annual NEE was measured from two sites between March 2014 and June 2015, where restoration commenced 10 years and 16 years prior to the start of this study, and the results were then compared to existing measurements from a near-pristine peatland. Existing NEE data (expressed as CO_2-C) from the near-pristine peatland indicated a C sink of 114 g m^{-2} yr^{-1}, and our estimates suggest that the older restored site (16 years) was also a NEE sink (71 g m^{-2} yr^{-1}). In contrast, the younger site (10 years) was a NEE source (80 g m^{-2} yr^{-1}). We critically assess the confidence of these measurements and also present these data in relation to other northern hemisphere peatlands to better understand the timeframe in which a peatland site can turn from a C source to a C sink after restoration.

KEY WORDS: carbon, eddy covariance, peatland restoration

INTRODUCTION

Northern peatlands are estimated to store around one third of total global terrestrial carbon (C) stocks (Scharlemann *et al.* 2014), and accumulate C at a rate of 19–23 g m^{-2} yr^{-1} (Billett *et al*. 2010, Gorham 1991, Yu 2012). Many peatlands have been disturbed through anthropogenic activities, with approximately 15 Mha of northern hemisphere peatlands drained for forestry (Holden 2004). In the UK, > 0.5 Mha of peatlands have been drained for non-native coniferous plantations (Cannell 1993).

The impacts of peatland drainage and degradation on carbon dioxide (CO_2) fluxes are relatively well understood; degraded peatlands have been demonstrated to be net sources of CO_2, releasing approximately 1 Pg yr^{-1} to the atmosphere globally (Ciais *et al*. 2013). In recent decades, due in part to the need for climate change mitigation, efforts have been made to restore ecosystem functioning characteristic of pristine peatlands to these degraded peatlands. These restoration efforts are aimed at reducing high CO_2 losses with the longer-term goal of increasing the C sink strength of these environments (Strack & Zuback 2013). In Scotland, restoration projects have focused on drained and afforested peatlands (Yamulki *et al.* 2013); however, there is relatively little empirical evidence to indicate whether restoration has been successful in increasing the C sink strength of these managed environments, or the trends in net ecosystem CO_2 exchange (NEE) after restoration has commenced.

Studies of peatland restoration – from land uses other than afforestation – suggest that the time taken for degraded peatlands to return to a net ecosystem C balance similar to that of a near-pristine site (~5 to ~50 years), will depend on the restoration practices employed and local site conditions (Strack & Zuback

2013). However, the focus of these published restoration studies has tended to be former peat cutting or horticultural sites (e.g. Strack & Zuback 2013). Far fewer studies, if any, have quantified the success and timescales of restoring the C balance of drained, afforested peatlands. A lack of year-round measurements and the use of infrequent, small-scale static flux chamber measurements have helped to constrain our uncertainty (Komulainen *et al*. 1999) but have prevented the development of robust annual C budgets. This is because temporally patchy or infrequent measurements may miss critically important transition periods (e.g. spring greening or autumn senescence) or may fail to capture important "hot moments" (*sensu* McClain *et al.* 2003) of biological activity. Higher frequency measurements have been found to increase the sensitivity of measurements in these periods (Lucas-Moffat *et al*. 2018). Eddy covariance (EC) can address these issues and reduce uncertainties by measuring continuously over all seasons and by integrating the flux over a larger spatial area.

In order to close these knowledge gaps, we present EC data collected between March 2014 and June 2015 on NEE from two previously afforested and drained peatlands in northern Scotland now undergoing restoration. Trends in CO_2 fluxes (gross primary production (GPP); ecosystem respiration (R); NEE) were compared against a near-pristine peatland in the same region and established on the same original soil type. Restoration of the sites from their degraded (i.e. drained and afforested) state began 10 and 16 years prior to the start of our measurements. Sufficient time has now passed since restoration commenced that we can now study the medium-term effects of restoration on the land-atmosphere exchange of CO_2. We asked: (1) can restoration of formerly afforested peatlands successfully restore the CO_2 sink function; and (2) whether the restoration process primarily affects GPP or R fluxes from the ecosystem. Finally, (3) we consider the implications of these findings for other restoration projects.

METHODS

The three sites are located within the Forsinard Flows National Nature Reserve, Caithness and Sutherland, Scotland. The reserve extends over 215 km^2 with elevations ranging from 44 to 580 m (Levy & Gray 2015). The climate of the Flow Country is generally cool and wet, with a mean annual precipitation of around 1000 mm and a mean annual temperature of ~ 8 °C (Kinbrace Weather Station; 58° 13' 59" N, 3° 55' 01" W, 103 m a.s.l.) (Met Office 2018). The study sites are: 1) '*Cross Lochs*': a near-pristine peatland with minimal management (Levy & Gray 2015). This site is characterised by typical peatland hummock and hollow microtopography; 2) '*Lonielist*': restoration started 10 years prior to commencement of NEE measurements; 3) '*Talaheel*': restoration started 16 years prior to commencement of measurements.

At the restoration sites, the average peat depth was approximately 2 m and water tables fluctuated between 0.5 and 0.7 m below the original surface of the peat. Both restoration sites had a similar mean water table depth below the furrow surface; Talaheel (0.11 ± 0.05 m), Lonielist (0.10 ± 0.02 m). However, the mean water content of the soil was higher at Talaheel (0.71 ± 0.05 m^3 m^{-3}) than at Lonielist (0.58 ± 0.04 m^3 m^{-3}). The mean peat depth at the near-pristine site was around 2.2 m, with a range of between 0.55 m and 7 m, and the mean water table depth was approximately 0.1 ± 0.06 m below the surface of the peat. The three sites are separated by no more than 10 km. Existing measurements were used at the Cross Lochs site (Levy & Gray 2015). At the Lonielist and Talaheel sites, new eddy covariance flux towers were established.

Study sites

The Cross Lochs site is located in the Forsinard Flows National Nature Reserve (58° 22' 13" N, 3° 57' 52" W, 210 m a.s.l.). Flux data are available from 2008 to 2014. The site is not directly managed but is subject to low levels of natural grazing from red deer (*Cervus elaphus L.*; Levy & Gray 2015). This site is near-pristine and consistent with the lowest levels of management found in peatlands in Scotland. Hereafter, this site is referred to as the '*near-pristine*' site. Further details of the site can be found in Levy & Gray (2015).

The Lonielist site (Figure 1) is located in the Forsinard Flows National Nature Reserve (Lat: 58° 23' 29" N, 3° 45' 59" W, 180 m a.s.l.) and was drained and planted between approximately 1983 and 1985. Flux data were collected from June 2014 to June 2015. During afforestation of the site, ploughing and drainage created significant microtopographical variations that still persist. Furrows are the wettest microform and are dominated by *Sphagnum* spp. and *Hypnum* spp. ridges. The ridges are formed by the peat that was thrown up when ploughing the furrows. The original surface is the strip of land that was not directly affected by ploughing, although it has been indirectly affected by peat compaction, and provides a drier microform that is dominated by *Ericaceae* spp., *Cyperaceae* spp. and *Poaceae* spp. The peat at Lonielist had a mean C content of 49.7 ± 0.28 % and a mean nitrogen (N) content of 1.73 ± 0.20 %. The

Figure 1. The Lonielist site in 2014. Vegetation is shorter than at the Talaheel site with small tussocks of *Eriophorum spp*., visible in the picture. Woody debris is clearly visible in each of the furrows and is more abundant than Talaheel. Photo: Graham Hambley.

site was restored from Sitka spruce (*Picea sitchensis*) and Lodgepole pine (*Pinus contorta*) forestry in 2003/04. The initial phase of restoration work occurred ten years prior to the start of our measurements. The restoration involved the felling of the non-native planted conifers and blocking of collector drains with peat or plastic pile dams to encourage the re-growth of peat forming vegetation species, such as *Sphagnum* spp. and *Eriophorum* (Hancock *et al*. 2018). During the restoration process, trees were felled, and left on-site as they were too small to harvest. In most cases they were placed in the plough furrows to help impede drainage but the plough furrows were not specifically blocked during this study period.

The Talaheel site (Figure 2) is located in the Forsinard Flows National Nature Reserve (58° 24' 49'' N, 3° 47' 52'' W, 196 m a.s.l.) and was drained and planted between approximately 1983 and 1985. Flux data were collected from March 2014 to March 2015. The data collection period was different at the two restored sites due to equipment availability at the Lonielist site. The Talaheel site also exhibits the same microtopography, with the same dominant vegetation as the Lonielist site. The peat had a mean C content of 50.1 ± 0.38 % and N content was 1.42 ± 0.23 %. The Talaheel site was also restored from Sitka spruce (*Picea sitchensis*) and Lodgepole pine (*Pinus contorta*) forestry in 1997/98 (Hancock *et al*. 2018). The restoration work occurred 16 years prior to the start of our measurements. The process of restoration was the same as at Lonielist, but it is worth noting that the trees were younger at this site and the canopy more open, due to the earlier felling time, which resulted in more peatland vegetation surviving post-felling and less brash resulting from felled to waste trees. As with the Lonielist site, restoration was on-going at the onset of flux measurements and measurements were undertaken while both sites had only undergone ditch blocking. New trial techniques, such as stump flipping and the flattening of microtopography were used at both Lonielist and Talaheel, post survey.

Eddy covariance measurements

High frequency EC measurements at the Lonielist site were made at 3 m height above the peat surface. The maximum fetch at the site exceeded 500 m and slopes were < 3 %. High frequency measurements were recorded at 10 Hz on a LI-550 Analyser interface unit (LI COR Biosciences, Nebraska, USA). A LI-7200 enclosed path Infra-Red Gas Analyser (IRGA; LI-COR Biosciences, Nebraska, USA) was paired with a HS-50 sonic anemometer (Gill Instruments Ltd, Hampshire, UK). Net radiation was measured with a CNR4 four component net radiometer (Kipp & Zonen, Delft, The Netherlands). Air temperature and humidity was measured with a HMP155 (Vaisala, Vantaa, Finland). Surface heat fluxes were measured using two HFP01s heat flux plates (Huskeflux, Delft, The Netherlands). Precipitation was measured using a 52202-tipping bucket rain gauge (R.M. Young, Michigan, USA). Power was supplied by a combination of solar panels, wind turbine and an EFOY Pro 800 methanol fuel cell (SFC Energy, Brunnthal, Germany). The power systems were installed approximately 5 m from the power in an easterly direction, with any data collected from this region rejected due to disturbance to the atmospheric structures.

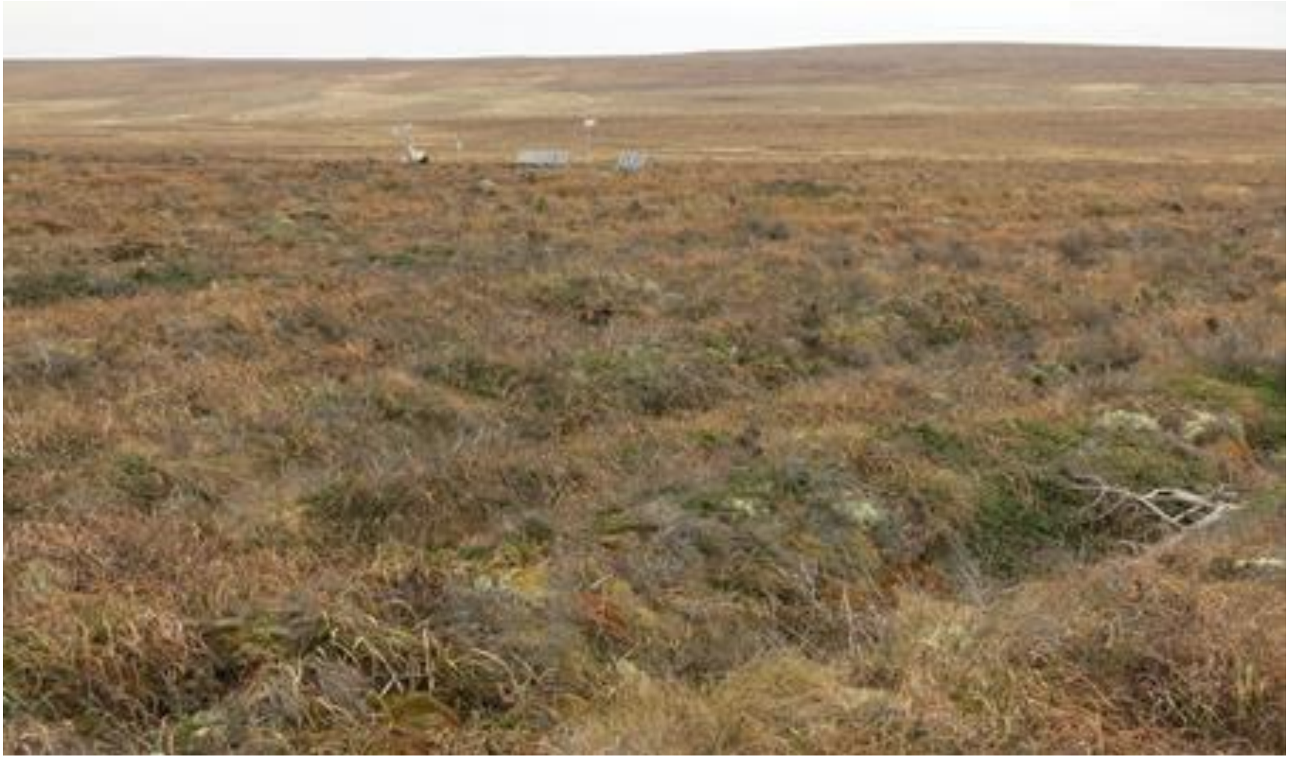

Figure 2. The Talaheel site with taller vegetation, such as *Eriophorum spp.*, present on the site. The microtopography on the site is visible in the foreground while further back the eddy covariance set up on the site can be seen. Photo: Graham Hambley.

Talaheel instrumentation

High frequency EC data at the Talaheel site were recorded at 3.4 m height above the peat surface. The fetch at the site exceeded 500 m and slopes were < 3 %. High frequency measurements were recorded at 10 Hz on a CR5000 analyser (Campbell Scientific, Logan, USA). A LI-7500 (LI-COR Biosciences Nebraska, USA) open path IRGA was paired with a CSAT sonic anemometer (Campbell Scientific, Logan, USA). The Burba correction for the additional sensible heat flux in the IRGA path (Burba *et al*. 2008) was not applied to these data due to the off-vertical mounting and generally mild environment, while also keeping the data consistent with the data gathered at Cross Lochs (Levy & Gray 2015) However, both systems were subjected to WPL correction for dilution and expansion due to warming. Net radiation was measured with a NR-Lite (Kipp & Zonen, Delft, The Netherlands). Air temperature and humidity was measured with a CS215 sensor (Campbell Scientific, Logan, USA). Surface heat fluxes were measured using two HFP01s heat flux plates (Huskeflux, Delft, The Netherlands). Precipitation was measured using an ARG100 tipping bucket rain gauge (EML, North Shields, UK). Power was supplied with a similar combination of power sources to Lonielist, installed approximately 20 m from the tower in an easterly direction, with any data collected from this region rejected due to disturbance to the atmospheric structures.

Eddy covariance processing

Data from the LI-COR systems were processed using the EddyPro software Version 6 (LICOR Biosciences, Nebraska, USA). Due to the combination of different systems used at the Talaheel site, data were processed using EdiRe (University of Edinburgh, Edinburgh, UK) and the programmes checked for consistency of processes. Data were processed to produce half-hourly flux estimates. High frequency data were despiked, and a humidity dependent time-lag applied (for the enclosed system). A planar fit coordinate rotation and linear least squares fit detrending tapered with a hamming window were applied prior to flux calculations. Frequency corrections were applied and checked via inspection of cospectra. Time lag compensation was calculated for both systems and applied accordingly. Gaps in the flux data were filled using the Reichstein *et al*. (2005) algorithm and implemented in the R package REddyProc (Reichstein & Moffat 2014). NEE was partitioned into GPP and R using the nocturnal partitioning approach (Reichstein *et al.* 2005). Energy balance closure was calculated at 30-minute and daily intervals using net radiation (R_n), ground heat flux (G), latent energy heat flux (LE) and sensible heat flux (H) data. For each site, annual NEE, GPP and R fluxes were calculated from the gap-filled fluxes.

Statistical analysis

A space for time chronosequence analysis was performed using the three EC towers. Using the chronosequence design, linear regressions were performed to test for a trend in the restoration sites using Matlab 2017b. The independent variable used in these regressions was the reciprocal of the time since restoration (in years), i.e. $Time^{-1}$. The near-pristine (Cross Lochs) site was given a nominal time since restoration of ∞. The dependent variables used in the regression were the annual mean flux of NEE, GPP or R for the three sites. Confidence intervals (CI) for the linear fit, slope and intercept were calculated for CI = 90 %, 75 % and 50 %.

We also consider how the three sites compare to the variation in CO_2 fluxes from existing northern hemisphere peatland sites as a function of latitude. These additional sites represent the response of minimally disturbed ‘intact’ northern hemisphere peatlands and were chosen as they are bogs in the northern hemisphere where CO_2 fluxes had been measured either through EC or chamber methods (Oechel *et al.* 2000, Aurela *et al.* 2002, Friborg *et al.* 2003, Sottocornola & Kiely 2005, Syed *et al.* 2006, Lund *et al.* 2007, Roulet *et al.* 2007, Flanagan & Syed 2011, Christensen *et al.* 2012, Strilesky & Humphreys 2012, Peichl *et al.* 2014, Helfter *et al.* 2015, Levy & Gray 2015, Pelletier *et al.* 2015). To assess if our three sites were within the bounds predicted by existing studies, we calculated the expected 90 % and 95 % CI for additional new observations based on the data from existing sites. We then determined whether the fluxes from our sites are within the CI predictions. This analysis was performed separately for NEE, GPP and R versus the latitude of the sites.

RESULTS

NEE, GPP and R fluxes

The 30-minute energy balance closure (e.g. LE + H versus R_n - G) was 92 % at the 16-year restoration (Talaheel) site and 83 % at the 10-year restoration (Lonielist) site. Annual NEE observations show that the 16-year restoration site (Talaheel) was a NEE sink (expressed as CO_2-C) of -71 g m^{-2} yr^{-1} and the 10-year restoration site (Lonielist) was a NEE source of 80 g m^{-2} yr^{-1} (Table 1, Figure 3). The six-year annual NEE mean from the near-pristine site (Cross lochs) was -114 g m^{-2} yr^{-1} (Levy & Gray 2015). The range in estimated mean annual NEE values across the sites was 194 g m^{-2} yr^{-1}.

Annual GPP (expressed as CO_2-C) for the two restoration sites was lower than the 575 g m^{-2} yr^{-1} measured at Cross Lochs (Table 1). Talaheel, the older restoration site, had higher GPP (551 g m^{-2} yr^{-1}) than Lonielist, the younger restoration site (501 g m^{-2} yr^{-1}) (Table 1). The difference between the GPP measured at Cross Lochs and Lonielist was 74 g m^{-2} yr^{-1}.

Annual R (expressed as CO_2-C) at both the restoration sites were higher than the 461 g m^{-2} yr^{-1} measured at Cross Lochs (Table 1). Talaheel, the older restoration site, had lower annual R (480 g m^{-2} yr^{-1}) than Lonielist, the younger restoration site (581 g m^{-2} yr^{-1}) (Table 1). The difference between the R measured at Cross Lochs and Lonielist was 120 g m^{-2} yr^{-1}.

Trends in NEE, GPP and R

Regressions of NEE with time since restoration indicate a return of the C sink with increasing time since restoration (Table 2). The regression analysis showed that the regression coefficients are statistically robust at a CI of 50 % (but not at the higher CI of 75 % and 90 %) (Table 2). Regressions of GPP with time since restoration indicate increasing productivity with time since restoration

Table 1. Annual carbon dioxide (CO_2) fluxes (expressed as CO_2-C) for Lonielist (restoration commenced in 2003/04), Talaheel (restoration commenced in 1997/98) and a near pristine blanket bog site *Values from the unmanaged site are a 6-year mean between 2008-2013 (Levy & Gray 2015).

Site	Description	NEE (g m^{-2} yr^{-1})	GPP (g m^{-2} yr^{-1})	R (g m^{-2} yr^{-1})
Lonielist	10-year restoration	80	501	581
Talaheel	16-year restoration	-71	551	480
Cross Lochs	Near-pristine	-114*	575	461

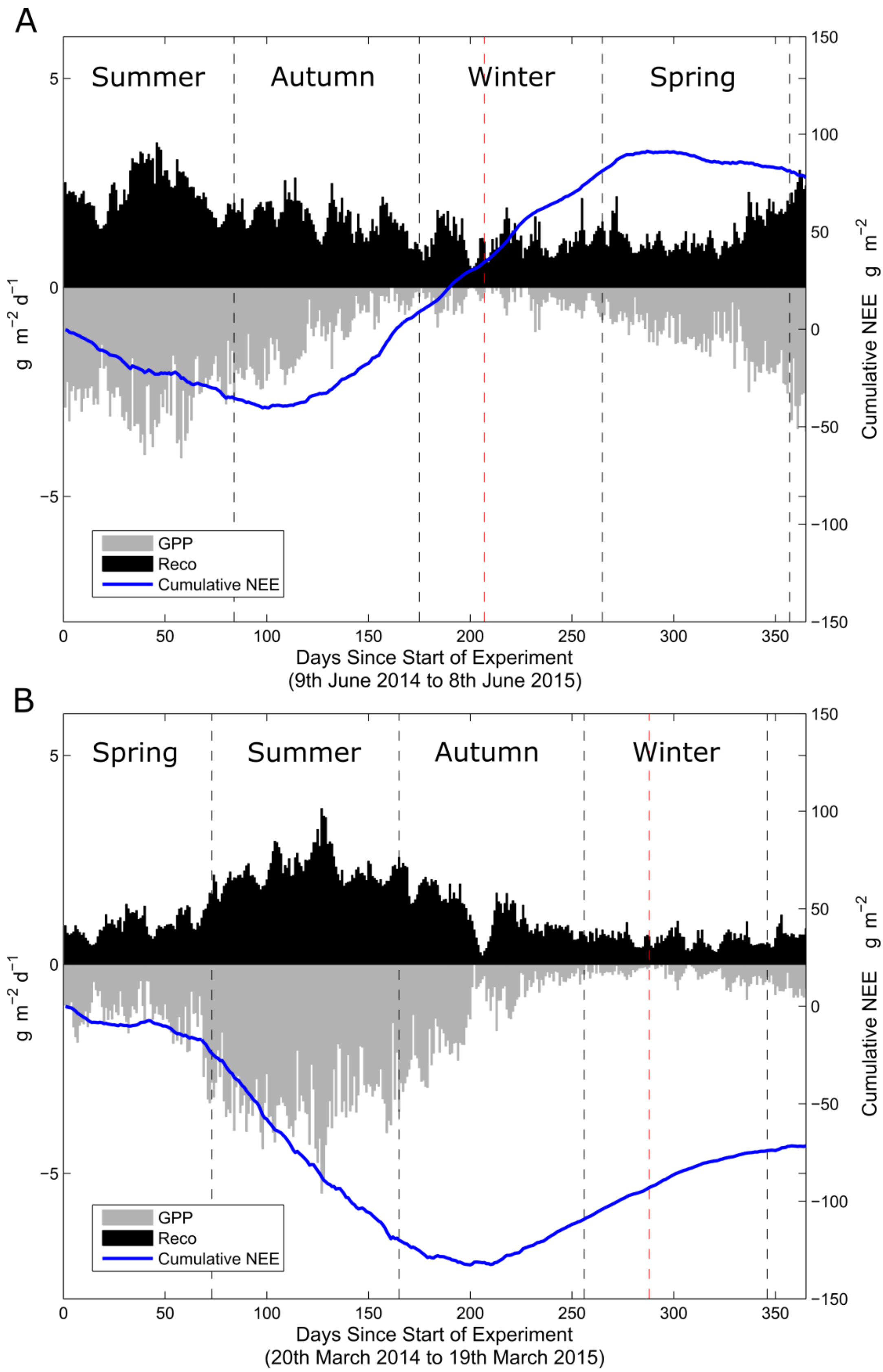

Figure 3. Daily GPP (grey) and R (black) flux from (A) Lonielist (restoration commenced in 2003/04) and (B) Talaheel (restoration commenced in 1997/98) during a full annual cycle, with cumulative NEE (blue) shown on the additional y-axis. Fluxes expressed as CO_2-C. Black dashed lines denote the seasons, while the red dashed line marks 1st January 2015. Different time periods are presented for each site due to the availability of equipment at each site.

(Table 2). The regression analysis also showed that the regression coefficients are statistically robust at a CI of 75 % (but not at the higher CI of 90 %). Regressions of R with time since restoration indicate decreasing annual respiration losses with time since restoration (Table 2). However, the regression analysis also showed that the regression coefficients are statistically robust at a CI of 75 % (but not at the higher CI of 90 %).

Comparison to other Northern hemisphere sites

The minimally disturbed 'intact' northern hemisphere peatlands (excluding the three sites used in this study) showed little dependence on latitude for NEE (Figure 4), although both GPP and R correlated strongly with latitude (Figure 4). Compared to other minimally disturbed 'intact' northern peatlands, both the near-pristine (Cross Lochs) and the 16-year-old restoration (Talaheel) sites showed no statistical differences in NEE, GPP or R at a 75 % CI. That is, both sites were within the 75 % CI for new observations. Similarly, for the 10-year restoration (Lonielist) site, there were no statistical differences in GPP or R at a 90 % CI. However, the 10-year NEE value at the restoration site was a statistical outlier falling outside the 95 % CI for new observations.

DISCUSSION

Carbon sink potential of restored peatlands returns within two decades after land-use change

The range in the mean annual CO_2 fluxes (expressed as CO_2-C) measured at our sites is 194 g m^{-2} yr^{-1}, or a factor of 10 larger than the mean annual C balance (19–23 g m^{-2} yr^{-1}) reported by Billett *et al*. 2010, Gorham 1991 and Yu 2011 for intact sites, although the latter includes CH_4 emissions and losses of dissolved organic carbon (DOC) that are not reported here. The near-pristine comparison site (Cross Lochs) had the largest annual NEE value (-114 g m^{-2} yr^{-1}) (Levy & Gray 2015). The 16-year restoration site (Talaheel) was also a NEE sink (-71 g m^{-2} yr^{-1}), while the 10-year-old restoration site (Lonielist) was the only NEE source (80 g m^{-2} yr^{-1}). The annual loss of CO_2-C from the 10-year restoration (Lonielist) site was less than that of a restored former horticultural peat extraction site in the Bois-des-Bel peatland complex in Canada (148 g m^{-2} yr^{-1}), which was restored in 1999/2000 (Strack & Zuback 2013). Annual NEE at the oldest restoration site is closest to the near-pristine site, which is in line with studies of other peatland sites undergoing restoration (e.g. Waddington *et al.* 2010). In this study, the switchover time from a net CO_2 source to a net CO_2 sink was estimated to be around 13 years (Figure 5) and is similar to other studies. For example, Günther *et al.* (2015) showed that the net GHG balance of a restored temperate fen peatland was similar to that of a pristine temperate fen peatland approximately 15 years after restoration.

Does restoration of afforested peatlands restore the CO_2 sink function?

These sites are representative of the peatlands within their respective flux footprints (Hill *et al.* 2017). However, extrapolation to the wider landscape cannot be robustly performed without additional replication, supporting measurements or the use of a more extensive chronosequence (Hill *et al.* 2017). The trend picked out by this space-for-time substitution suggests that NEE shifts towards a stronger net CO_2 sink as time since restoration increases. However, crucially, this analysis is only valid at a CI of 50 % (Table 2 and Figure 5). Despite this level of confidence being below commonly accepted criteria (e.g. 90 to 95 %) – that there is a regression at all with three samples strongly suggests that with more replicates a statistically robust correlation may emerge.

Table 2. Fitted slope and intercept coefficients with confidence intervals at 90, 75 and 50 %. Fits are provided for dependent variables (y): NEE, GPP and R. The independent variable (x) was the reciprocal of the time since restoration in years (*i.e*. 1/Time), e.g. y = slope / Time + Intercept. For the Cross Lochs (near-pristine) site, the time since restoration was set at infinity.

Flux	Slope	Slope CI (%)			Intercept	Intercept CI (%)		
		90	75	50		90	75	50
NEE	1812	± 5588	± 2137	± 885	-133	± 380	± 145	± 60
GPP	-704	± 1589	± 608	± 252	580	± 108	± 41	± 17
R	1143	± 2500	± 956	± 396	452	± 170	± 65	± 27

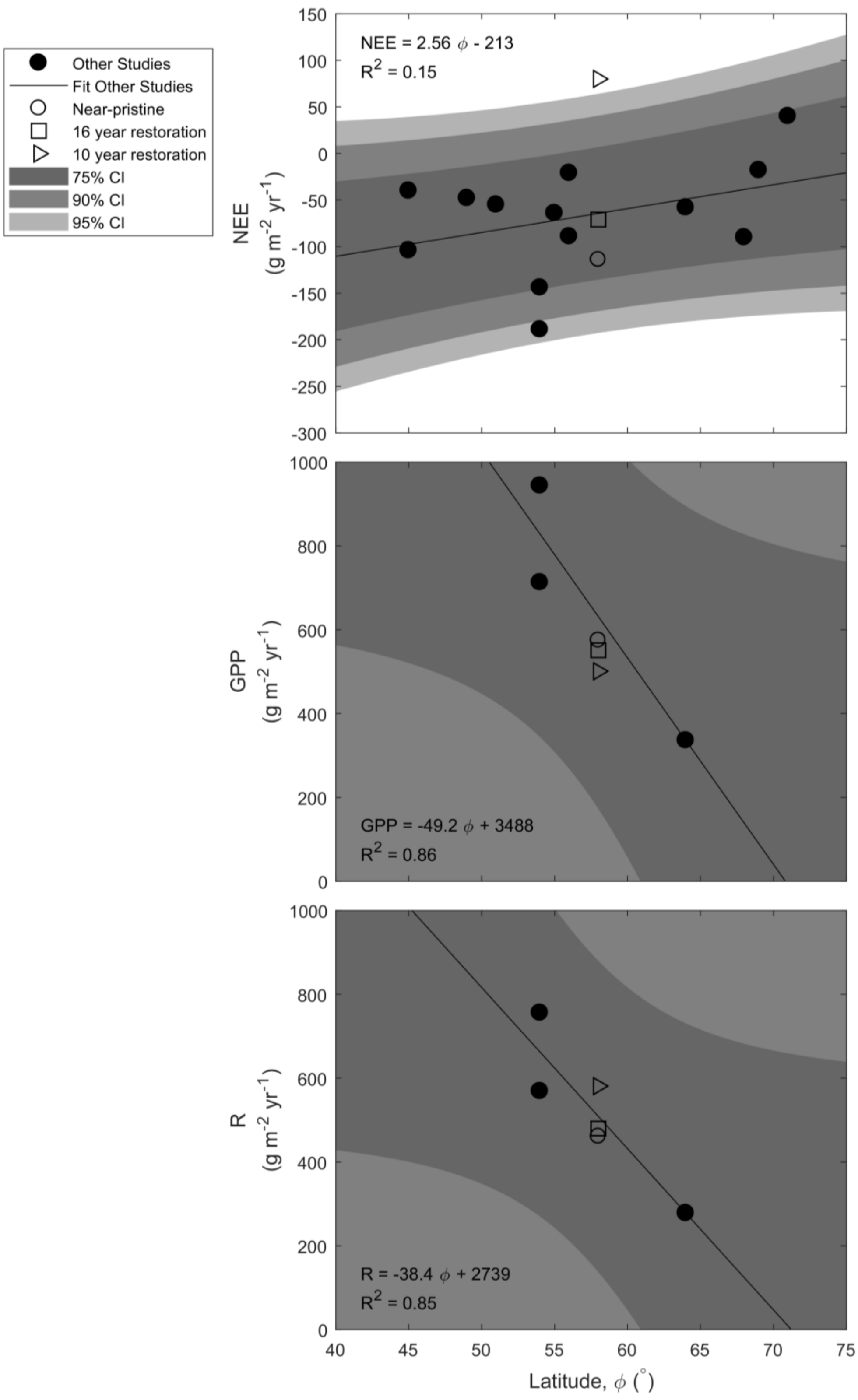

Figure 4. Annual NEE, GPP and R at "intact" peatland sites in the Northern hemisphere (black dots) (Oechel *et al*. 2000, Aurela *et al*. 2002, Friborg *et al*. 2003, Sottocornola & Kiely 2005, Syed *et al*. 2006, Lund *et al*. 2007, Roulet *et al*. 2007, Flanagan & Syed 2011, Christensen *et al*. 2012, Strilesky & Humphreys 2012, Peichl *et al*. 2014, Helfter *et al*. 2015, Levy & Gray 2015, Pelletier *et al*. 2015). Fluxes expressed as CO_2-C. Linear fits are shown based on these natural peatland sites (black line). Based on the linear fits 95 %, 90 % and 75 % confidence intervals (CI) for new observations are predicted (shaded areas). The open symbols show the annual estimates for NEE, GPP and R from the near-pristine, 16-year restoration and 10-year restoration sites from this study. Note that these three sites were not used in the curve fits.

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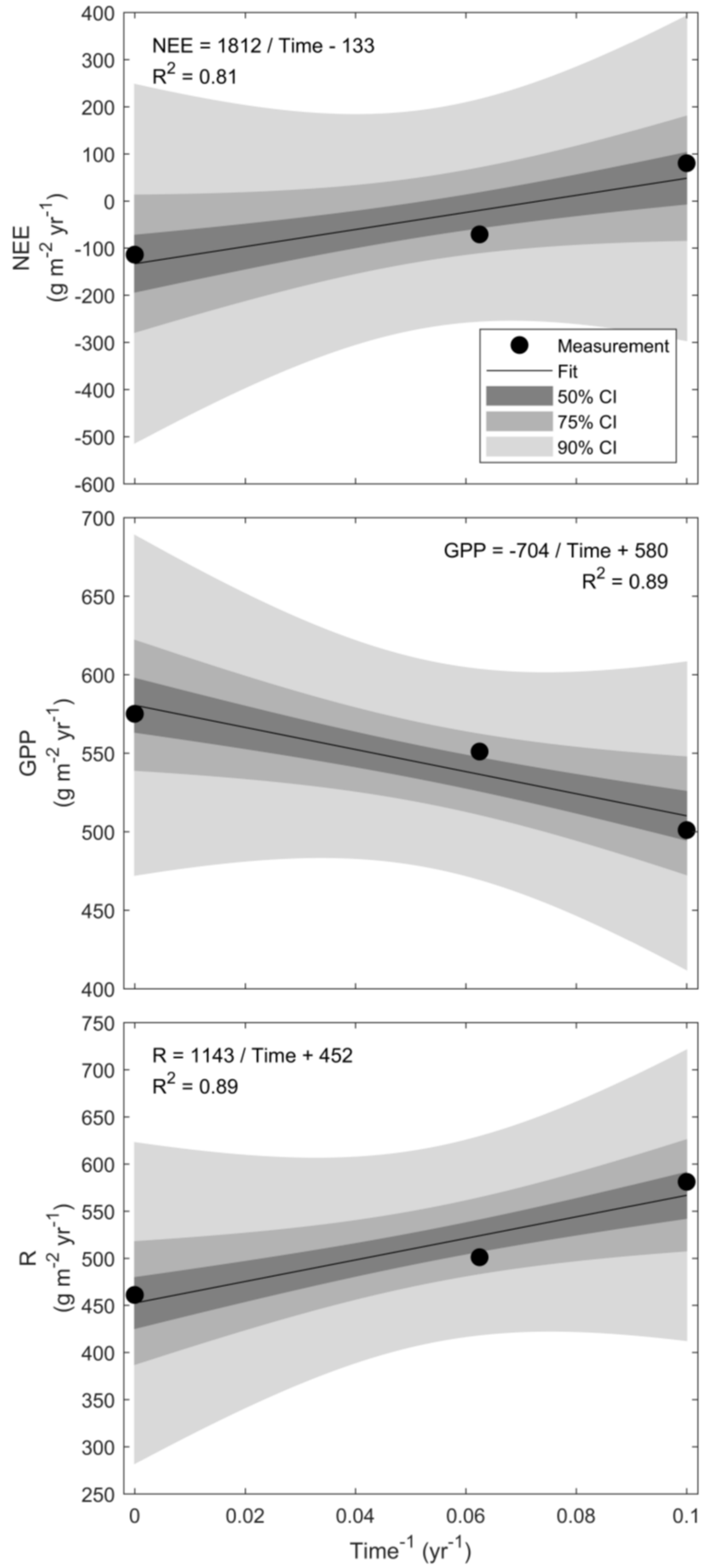

Figure 5. Black points indicate annual NEE (panel a), GPP (panel b) and R (panel c) of the three sites plotted against the reciprocal of their time since restoration ($Time^{-1}$). Fluxes expressed as CO_2-C. The value of $Time^{-1}$ is: Cross Lochs ($\infty^{-1} = 0$), Talaheel ($16^{-1} = 0.063$) and Lonielist ($10^{-1} = 0.1$). The line of best fit (black line) for the dependent variables: NEE (panel a), GPP (panel b) and R (panel c). Shaded areas correspond to the 90 %, 75 % and 50 % confidence intervals (CI) for the line of best fit.

A metanalysis by Wilson *et al*. (2016a) did not show any relationship between NEE and time since re-wetting although the authors did note that their emission factors assume that rewetted organic soils immediately behave like undrained organic soils. A lack of long term datasets, providing clear temporal trends add to this uncertainty (Wilson *et al.* 2016b). The data provided in this research helps to reduce some of these uncertainties. We also note that most studies do not publish CI for flux comparisons, and so have little statistical power (Hill *et al.* 2017).

To explore the effects of restoration in a wider context, we considered whether these sites are statistical outliers compared to other minimally disturbed 'intact' northern hemisphere peatlands (Figure 5). Our analysis plots mean annual NEE against latitude, as it would be expected that sites at lower latitudes would be greater sinks along a decreasing latitudinal NEE trend (Van Dijk & Dolman 2004, Yuan *et al*. 2009). Mean annual NEE fluxes from the near-pristine (Cross Lochs) and 16-year restoration (Talaheel) sites were both within the 50 and 75 % CI of each other, and therefore in-line with the expectation for other northern hemisphere peatlands. However, it could be argued that Talaheel cannot be considered "intact" in terms of CO_2 sink functioning due to the evident effects of disturbance at the site. The nearest comparable study site is Auchencorth Moss near Edinburgh (approximately 400 km south of these sites), where mean annual NEE over 11 years was -64 g m^{-2} yr^{-1}, with a range of -142 to -5.2 g m^{-2} yr^{-1} (Helfter *et al*. 2015). This site was drained over 100 years ago and was re-vegetated by allowing ditches to naturally infill over time (i.e. without clearing drains as part of routine maintenance), thereby slowing water loss from the site. Research in a Siberian bog near Tomsk, Russia (56° N) showed a NEE sink of -89 g m^{-2} yr^{-1} (Friborg *et al*. 2003), which is similar to the value observed at our 16 year old restoration (Talaheel) site. In contrast, NEE at the 10-year restoration (Lonielist) site was outside the expected 95 % CI, suggesting that this site is a larger than expected source of CO_2. This analysis adds additional weight to the earlier (statistically marginal) expectation that younger restored afforested peatlands will be net C sources.

Does the restoration process primarily affect productivity or respiration fluxes?

Considering the space for time chronosequence, a similar trend to NEE was evident in the GPP data, with the near-pristine site being the most productive and the 10-year-old restoration (Lonielist) site the least productive (Table 1). Additionally, the 10-year-old restoration site had the largest respiration fluxes, while the near-pristine site had the lowest respiration fluxes (Table 1). In the space for time chronosequence analysis of the sites, both GPP and R showed statistically significant correlations at the 75 % CI (Table 2, Figure 5). Whilst the inter-site range in GPP was just 74 g m^{-2} yr^{-1}, the equivalent range in R was 120 g m^{-2} yr^{-1}, suggesting that the improved sink was due to both increasing GPP, but also a greater decrease in R. Therefore, further studies should focus on shifts in the balance of GPP and R in order to understand the success of restoration, similar to findings by other research where NEE was more strongly influenced by R than GPP (Wilson *et al.* 2016b)

Interestingly, in the wider context of other minimally disturbed 'intact' northern hemisphere peatlands the differences in the sites were not significant (Figure 4). This is because the range of mean annual NEE for northern hemisphere sites is relative small; both GPP and R exhibit a wide range in values (Figure 4). This trend is to be expected due to the latitudinal variations in light, temperature and precipitation. Previous research has suggested that GPP drops off more rapidly at higher latitudes than R, which leads to a general trend of decreasing NEE with increasing latitude (Van Dijk & Dolman 2004, Yuan *et al*. 2009). This has been suggested to explain the larger source or smaller sink status at higher latitudinal peatlands such as those in the arctic (Oechel *et al*. 2000, Aurela *et al*. 2002), however, our basic analysis does not support this NEE trend at higher CI (Figure 4).

Implications for restoration of afforested peatlands

Our data, one of very few datasets from previously afforested peatlands, is in general agreement with previous research that suggests restoring peatlands reduces CO_2 losses to the atmosphere (Nykänen *et al*. 1995, Waddington & Price 2000, Waddington *et al*. 2002, Ojanen *et al*. 2010). Our study also indicates that the restoration of ecosystem functioning is likely to take longer than the 6–10 years previously proposed from research in Canada (Waddington *et al.* 2010). However, recent work has suggested that restoration success is site specific and is largely dependent upon the starting point of restoration and the previous land use (Renou-Wilson *et al*. 2019). In this study, Talaheel was closer to a pristine site at the onset of restoration and thus it would be expected that restoration of the net ecosystem CO_2 sink would occur more quickly than at Lonielist. Similarly, vegetation studies at our oldest restoration site (Hancock *et al.* 2018) showed that significant vegetation differences from open bog remained after 14 years, even though there was evidence that the moisture regime, as indicated by plant species, had largely recovered. This is broadly in line with findings of other restoration studies (Haapalehto *et al.* 2017) and underlines the need for long term monitoring of restoration sites (Haapalehto *et al.* 2017, Hancock *et al.* 2018). For both our study sites that are undergoing restoration, the plough furrows were never blocked and data suggests that water tables are still depressed well below the original peat surface compared to the Cross Lochs site. Blocking these furrows and raising water tables should speed up the restoration of these peatland habitats.

Study limitations and future research

Although the data have suggested that the restoration efforts are successful in restoring the ecosystem C sink, the strength of the statistical analysis could be improved. These improvements could be achieved with a longer time series (to capture inter annual variability), additional concurrently running towers, and data sources other than EC. Although appropriate corrections were applied, further research should be undertaken to fully understand the effects of the different IRGAs used to quantify NEE. The challenge of attaining good statistical power is particularly acute in peatland ecosystems, where the net fluxes are small because NEE is the difference between two comparatively large opposing fluxes in R and GPP but varies with hydrological and climatic conditions (Wright *et al*. 2013, Armstrong *et al*. 2015, Buczko *et al*. 2015). The combination of high variability of small fluxes leads to small 'effect sizes' and a need for improved spatiotemporal sampling (Hill *et al.* 2017).

While these ecosystems appear to return to a net CO_2 sink over time, other pathways (e.g. aqueous fluxes and other trace gases) could alter the net C budget of these ecosystems. Methane remains a poorly understood component in these restored ecosystems although research generally points towards increased CH_4 emissions post restoration (e.g. Koskinen *et al.* 2016). Therefore, further research is required to understand these pathways and the effect that restoration has on C losses/gains.

Coherent features on the land surface, such as the regular microtopographic forms at Talaheel and Lonielist, have the potential to cause flow disturbances and thus deviations from the theory on which eddy covariance is based. This could cause several issues, including biases in the frequency corrections applied to the fluxes. To check for this, we inspected the spectra/cospectra from the sonic anemometer's temperature measurements (i.e. the highest frequency response). These spectra were compared to the theoretically expected frequency model. This investigation indicated that there were no particular concerns in this regard (over and above the usual caveats for eddy covariance). Therefore, we have no reason to believe (or a mechanism for) that a systematic bias exists between the sites, driven by differences in the physical microtopographic features.

Restoration is on-going at these sites with other restoration techniques, such as stump flipping and microtopography re-alignment, being used to help speed up the restoration process and more rapidly return the C sink function in these sites. However, further monitoring of these sites is required to determine the effect of these actions on NEE.

Little empirical annual NEE data exists from previously afforested northern peatlands undergoing restoration. Moreover, few peatland restoration sites are large enough for the use of eddy covariance methods, meaning most studies that have examined NEE from restored peatlands are based upon chamber fluxes. Typically, chamber measurements are carried out at lower temporal frequencies than eddy covariance with higher frequency measurements undertaken in the growing season seasonally biasing the data. The data we present here represent the first annual measurements of NEE using eddy covariance on peatlands restored from plantation forestry. Our study suggests that restoration of formerly afforested peatlands can lead to restoration of the CO_2 sink approximately 15 years after the start of restoration. However, this study is based on only two restoration sites, each measured for a single year. Additional EC towers and longer records are likely to improve the confidence in restoration outcomes with regards to C sequestration.

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