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LETTER

Prompt active restoration of peatlands substantially reduces climate impact

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Supplementary material for this article is available online

Abstract

Restoration of peatlands after peat extraction could be a benefit to the climate system. However a multi-year ecosystem-scale assessment of net carbon (C) sequestration is needed. We investigate the climate impact of active peatland restoration (rewetting and revegetating) using a chronosequence of C gas exchange measurements across post-extraction Canadian peatlands. An atmospheric perturbation model computed the instantaneous change in radiative forcing of CO_2 and CH_4 emissions/uptake over 500 years. We found that using emission factors specific to an active restoration technique resulted in a radiative forcing reduction of 89% within 20 years compared to IPCC Tier 1 emission factors based on a wide range of rewetting activities. Immediate active restoration achieved a neutral climate impact (excluding C losses in the removed peat) about 155 years earlier than did a 20 year delay in restoration. A management plan that includes prompt active restoration is key to utilizing peatland restoration as a climate change mitigation strategy.

Introduction

Peatlands play an important role in the global carbon (C) cycle. While their annual uptake of C is relatively small compared to many other ecosystems, the persistent uptake and maintenance of the large store of sequestered atmospheric carbon dioxide (CO_2) in peatlands has led to net climate cooling due to their long-term negative radiative greenhouse gas (GHG) forcing (Frolking *et al* 2006, Frolking and Roulet 2007). Radiative forcing of a peatland is the difference between the atmospheric CO_2 sequestered since peatland formation (millennia) and recent perturbations (decades) to methane (CH_4) fluxes (Frolking *et al* 2006). Northern peatlands are estimated to contain ~500 Gt C (Yu *et al* 2010, Scharlemann *et al* 2014) which is approximately 58% of the amount contained in the atmosphere (402.8 ± 0.1 ppm CO_2 in 2016 ~862 Gt C) (Dlugokencky and Tans 2017). However, more than 50% of the global wetland area, including peatlands, has been lost since 1700 CE because of land use change (Davidson 2014). Roughly 10% of remaining global peatlands are degraded by land use changes (such as peat extraction, agriculture, grazing and forestry) representing a carbon stock of 80.8 Gt C that is being diminished at a rate of ~1.91 Gt C annually (Leifeld and Menichetti 2018). Degradation results in mineralization of stored peat, releasing large amounts of CO_2, but generally reducing CH_4 to minimal levels except from drainage ditches, which can act as hotspots for CH_4 emissions (Wilson *et al* 2016).

Soil C sequestration and avoided GHG emissions through restoration of degraded peatlands are climate change mitigation strategies shown to be more cost effective in terms of nitrogen addition required and land area demand than rehabilitating agricultural land (Leifeld and Menichetti 2018). However, the success of peatland restoration for long-term C management through its impact on radiative forcing is not well known. A few studies have examined the GHG fluxes from restored peatlands using periodic (non-continuous) chamber measurements (e.g. Strack and Zuback 2013, Wilson *et al* 2016, Renou-Wilson *et al* 2019, Swenson *et al* 2019) but the spatial and temporal extrapolation required to achieve an annual balance introduces errors (Bubier *et al* 1999), limiting its utility to investigate climate impacts.

A full accounting of GHG emissions from the drainage and rewetting of organic soils (i.e. peatlands) is required in national GHG inventory reports to the UNFCCC (IPCC 2014). The IPCC methodology uses a tiered approach for emission accounting based on the scale and quality of available data. The simplest reporting method, Tier 1, applies default values for emission/removal factors multiplied by the areas of land-use change affected by specified activities to estimate emissions for the project or sector of interest. For managed wetlands, the default emission factors provided are often averages from chamber GHG flux measurements gathered for an eco-region (e.g. boreal, temperate and tropical). The Tier 2 approach is similar conceptually to Tier 1, but substitutes emission factors from country-specific emissions, usually obtained through scale-appropriate empirical measurements. Tier 3 is the most detailed approach and involves the simulation of land-use change impacts based on models of the underlying processes controlling emissions.

With Tier 1, the IPCC uses a global warming potential (GWP) metric approach to compare the relative climate impact of GHGs with different atmospheric lifetimes and radiative efficiencies. Emissions/removals of different GHGs are converted to an equivalency in metric tonnes of CO_2 (CO_2-eq). The sign of the CO_2-eq determines whether the perturbation to the system in question (e.g. ecosystem, sector) has a net warming or cooling effect on global climate. A major shortcoming of the GWP is that it treats emissions as single pulses rather than continuous and evolving emissions or removals through biosphere-atmosphere interactions (Neubauer and Megonigal 2015). As well, the time integration for GWPs is arbitrary and does not recognize the time integration of a continuous gas exchange; a 100 year integration horizon was adopted by the Kyoto Protocol and continues to be in effect (Lashof 2000). Less common, but more informative, is the approach of directly modelling the atmospheric dynamics of GHGs (Frolking *et al* 2006, Frolking and Roulet 2007, Lohila *et al* 2010, Neubauer 2014, Neubauer and Megonigal 2015, Helbig *et al* 2017, Dommain *et al* 2018), which uses time integrations more appropriate for continuous ecosystem exchanges. An atmospheric perturbation model driven by continuous measurements of net GHG fluxes can account for the temporally variable rates of GHG exchange found in ecosystems (Neubauer and Megonigal 2015).

We use the case study of the Canadian horticultural peat moss industry to quantify the net climate impact of restoring peatlands. Approximately 34 000 ha of Canadian peatlands are, or have been, drained for peat extraction, of which 18 000 ha are under active management (ECCC 2018). Land-use regulations vary in detail and extent by province but there is now a need to demonstrate commitment to restoration before new sites can be opened (Rochefort *et al* 2003). Restoration planning that meets the conditions for responsible horticultural peat moss production certification is increasingly an industry and consumer expectation. The IPCC definition of restoration is a process of assisting the recovery of an ecosystem that has been degraded which, in the case of drained peatlands, always has to include rewetting (IPCC 2014). The Canadian horticultural peat moss industry employs an active restoration strategy that incorporates the moss layer transfer technique (Graf and Rochefort 2016) in addition to rewetting. A multi-year continuous measurement study of ecosystem-scale active restoration of a post-extraction peatland showed annual net CO_2 sequestration within 14 years (Nugent *et al* 2018). To quantify the efficiency of peatland restoration actions, however, the time spent in an unrestored state needs to be accounted for. Here, we used a space-for-time substitution from an eddy covariance tower series at an undisturbed, 2 unrestored, and 2 restored post-extraction peatlands in Canada with an atmospheric perturbation model to evaluate the net ($CO_2 + CH_4$) radiative forcing of restoration actions. Our Tier 2 level results are compared with the net radiative forcing of average rewetting actions provided by IPCC Tier 1 emission factors, and also with not restoring post-extraction peatlands. We hypothesize that active restoration (Tier 2) will achieve a neutral climate impact more quickly than average rewetting actions (Tier 1), and that not restoring will cause an increasing positive radiative forcing over a 500 year timeframe.

Methods

Data sources

This study is based on net ecosystem flux measurements of CO_2 (NEE), CH_4 and dissolved organic carbon (DOC) from horticulture-extracted peatlands. The study sites were part of a paired unrestored/restored eddy covariance tower project in eastern (Québec) and western (Alberta) Canada that took place between July 2013 and November 2016 (Nugent *et al* 2018, Rankin *et al* 2018). The active restoration approach, known as the moss layer transfer technique, applied at the study sites incorporates site re-grading, rewetting (ditch blocking and/or infilling), revegetating with material from donor peatlands, protection with straw mulch, and phosphate fertilization where required (see Graf and Rochefort, 2016 for more details). The eastern restored site, Bois-des-Bel, has undergone periodic flux monitoring since being restored in the autumn of 1999 (e.g. Petrone *et al* 2003, Waddington *et al* 2003, Waddington and Day 2007, Waddington *et al* 2008, Waddington *et al* 2010, Strack and Zuback 2013, Nugent *et al* 2018). The well-studied Mer Bleue bog (1998 to present eddy covariance record; Roulet *et al* 2007) located near Ottawa, ON, Canada was used as a representative undisturbed peatland. Mer Bleue is currently the best record to use as the endpoint of the restoration trajectory, as its long-term record captures the wide range in variability when estimating a mean flux. Greenhouse gas flux monitoring occurred continuously over the growing season/year at the eastern and western Canadian paired unrestored/restored sites and undrained peatland, and a standard data post-processing methodology was used (Nugent *et al* 2018). Main site characteristics of the study sites are presented in table S1.1 (available online at stacks.iop.org/ERL/14/124030/mmedia), site-specific measurement techniques and instrumentation in table S1.2, site-specific gap-filling methods for CO_2 and CH_4 in table S1.3 and annual CO_2, CH_4 and DOC fluxes (mean ± 95%CI) in g C m^{-2} yr^{-1} in table S1.4. The 95% confidence interval of gap-filling was calculated based on error in determining the friction velocity threshold (Papale *et al* 2006), as well as a random measurement error estimate (Richardson *et al* 2006). A recent study comparing restored site fluxes of CO_2 and CH_4 at the plot-scale determined no significant difference between eastern and western Canada (Strack *et al* 2016). As such, we compiled the data listed in table S1.4 into an unrestored and restored chronosequence that reflects the management history of Bois-des-Bel; that is, extraction over a ten-year period followed by 20 years without management (unrestored period) prior to restoration. We chose to not incorporate nitrous oxide (N_2O) fluxes into our GHG chronosequence because we had insufficient data from our study sites to make a defensible estimate of annual exchange (but see supporting information section S3). Chamber fluxes at the restored Bois-des-Bel site determined an N_2O flux that was most often not distinguishable from zero (data not shown), similar to the western Canada unrestored and restored sites (Brummell *et al* 2017). A study of Estonian peatlands undergoing extraction found negative N_2O fluxes at their undrained reference sites (Salm *et al* 2012). It seems likely that N_2O fluxes are a minor component of the total GHG balance when compared to the much larger CO_2 and CH_4 fluxes. For comparison, IPCC Tier 1 assumes a minimal N_2O flux when drained (0.03 g N m^{-2} yr^{-1}) and a negligible flux after rewetting (IPCC 2014).

Modelling radiative forcing

Radiative forcing was computed with an atmospheric perturbation model originally presented in Frolking *et al* (2006). The model has been updated with revised radiative efficiencies, atmospheric lifetime numbers, and indirect radiative forcing effects in accordance with the latest IPCC synthesis report (Myhre *et al* 2013). As well, the CO_2 portion of the model uses impulse response parameters from Joos *et al* (2013) instead of an earlier parameterization. Sustained CO_2 and CH_4 fluxes estimated from the chronosequence of measured exchanges are treated as perturbations to a series of linear non-interacting, first-order atmospheric reservoirs (see figure 1 in Dommain *et al* 2018 for general structure of the model). The net ($CO_2 + CH_4$) radiative forcing (RF_{net}) was calculated as the sum of the individual gas contributions:

$$RF_{net}(t) = \sum_{i=0}^{5}\left(\xi_i A_i f_i \cdot \int_0^t \Phi_i(t')e^{(t'-t)/\tau_i}dt'\right), \quad (1)$$

where ξ_i is a multiplier for indirect effects, A_i is the radiative efficiency of greenhouse gas i, f_i is the fractional multiplier for the net flux into reservoir i, $\Phi_i(t')$ is the net flux of a greenhouse gas i into the atmosphere at time t', and τ_i is the adjustment or residence time of the reservoir i; for model parameter values, see table 3 in Dommain *et al* (2018).

The atmospheric perturbation estimates were based on the chronosequence of CO_2, CH_4 and DOC fluxes detailed in table 1; i.e. replacing the IPCC Tier 1 default values with the observed exchanges. The proportion of DOC exported that is ultimately emitted as CO_2 was chosen to be 0.9 ± 0.1, the value proposed by the IPCC for calculating Tier 1 default annual emissions of CO_2 due to DOC export (IPCC 2014). In a review of the fate of waterborne carbon from drained and rewetted peatlands, Evans *et al* (2016) concluded that current observations support a value of 0.9 ± 0.1. Applying this number ignores, however, that DOC breakdown can occur over a long temporal continuum along the river-lake-estuary-ocean system (Evans *et al* 2016). The CO_2 input into the model (CO_2_tot) is thus calculated as:

$$CO_2\_tot = CO_2 + 0.9*DOC. \quad (2)$$

The CH_4 input into the model is calculated as:

$$CH_4\_tot = 0.95*CH_4 + 0.05*CH_4 - Ditch. \quad (3)$$

However, because the CH_4 emissions from drainage ditches at our study sites are already included in the annual CH_4 flux measured with eddy covariance, the ditch term in equation (3) is set to zero and the CH_4 input into the model is the measured value.

Table 2 outlines the Tier 2 scenarios run following model spin up (S2). For the unrestored and post-restoration periods, the 95% confidence range of the fluxes in table 1, the confidence interval on the fraction of DOC converted to CO_2 (0.9 ± 0.1), and the

Table 1. Canadian post-extraction peatland C fluxes compared to IPCC Tier 1 emission factors. Our study results are a space-for-time (chronosequence) collation of empirical measurements. IPCC Tier 1 emission factors are for drained peatlands managed for extraction and rewetted organic soils. Negative values are removal by the ecosystem while positive values are emission to the atmosphere.

		IPCC Tier 1 emission factor		Our study	
		Climate/vegetation zone	Mean (95% CI) ($g C m^{-2} yr^{-1}$)	Chronosequence	Mean (95% CI) ($g C m^{-2} yr^{-1}$)
Drained/unrestored	CO_2	Boreal and temperate	280 (110–420)	UNR-1 year	445 (426–460)
				UNR-15 year	216 (132–300)
	DOC	Temperate	31 (19–46)	UNR	35 (26–45)
	CH_4	Boreal and temperate	0.5 (0.1–0.8)	UNR	0.5 (0.3–0.7)[b]
	CH_4-Ditch	Boreal and temperate	40.6 (7.6–73.5)[a]		n/a
Rewetted/restored	CO_2	Temperate poor	−23 (−64–+18)	RES-1 year	504 (291–717)
				RES-4 year	145 (−12 to 302)
				RES-15 year	−90 (−110 to 69)
				RES-30 year	−73 (−136 to −9)
	DOC	Temperate	24 (14–36)	RES-15 year	8 (6–10)
				RES-30 year	17 (14–20)
	CH_4	Temperate poor	9.2 (0.3–44.5)[c]	RES-1 year	1.1 (0.5–1.7)
				RES-4 year	4.3 (0.7–7.9)
				RES-15 year	4.4 (4.2–4.5)
				RES-30 year	6.0 (2.0–10.0)

[a] Site-level fractional cover of ditch is estimated to be 0.05 based on the mean of six studies in the land-use category reporting CH_4 emissions.
[b] CH_4 emissions from drainage ditches are included.
[c] CH_4 emissions from former ditches are not treated separately after rewetting.

Table 2. Atmospheric perturbation model scenario inputs. Scenario descriptions reference table 1.

Tier	Scenario	Description
Tier 1	Average rewetting	Drained emission factors over 20 years Rewetted emission factors over 480 years
	Immediate average rewetting	Rewetted emission factors over 500 years
	No rewetting	Drained emission factors over 500 years
Tier 2	Active restoration	Unrestored chronosequence over 20 years Restored chronosequence over 480 years
	Immediate active restoration	Restored chronosequence over 500 years
	No restoration	Unrestored chronosequence over 500 years

standard error on the indirect effects multiplier for CH_4 (1.65 ± 0.3) were used to establish an uncertainty bound. This includes sustained maximum (minimum) CO_2 removal and minimum (maximum) CH_4 emission to the atmosphere.

The modified version of the model that does not include pre-extraction was used to run the IPCC emission factors detailed in table 1 as time-invariant fluxes. Emission factors, taken from the IPCC 2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC 2014), were available for the categories: (1) drained Organic Soils: Peat Extraction, and (2) rewetted Organic Soils as an average with a 95% confidence interval. Emission factor units were standardized to $g C m^{-2} yr^{-1}$ to facilitate inter-comparison in table 1. The Tier 1 scenarios that were simulated with the modified model and uncertainty bounds computed using the same method as Tier 2 are presented in table 2.

The model output, RF_{net}, is an annual time series of the radiative forcing due to cumulative GHG emissions or removals from an initial year. Following Frolking *et al* (2006), the time that RF_{net} changes from positive (net warming) to negative (net cooling) is referred to as the radiative forcing switchover time. For this study, we discuss the instantaneous switchover time relative to radiative forcing in 1980 rather than the cumulative radiative forcing switchover time, which reflects GHG dynamics integrated over the history of the peatland (Neubauer 2014).

Results

Chronosequence establishment

Our measurements in unrestored post-extraction peatlands show that not restoring after extraction leads to large CO_2 release to the atmosphere, both initially (UNR-1 year) and more than a decade later (UNR-15 year; figure 1). CO_2 emissions were lower at the older unrestored site due to some spontaneous plant regeneration in the drainage ditches and wetter areas of the site (Rankin *et al* 2018). However, the lowest annual CO_2 emission from the older unrestored site is more than twice as much as the average uptake at our

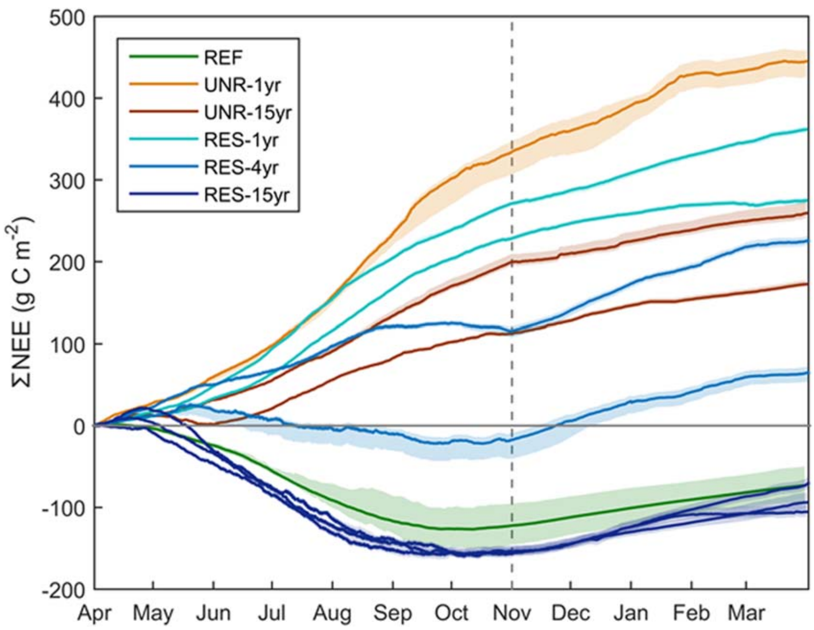

Figure 1. Ten site years of annual cumulative net CO_2 flux at Canadian post-extraction peatlands.

reference undrained peatland, Mer Bleue (REF) (figure 1).

NEE at unrestored (UNR) and actively restored (RES) peatlands are compared to a reference (REF) peatland, Mer Bleue. Displayed are the first year of UNR-1 year, two consecutive years of UNR-15 year, two consecutive years of RES-1 year, two years of RES-4 year measured at adjacent sites in the same year, three consecutive years of RES-15 year and the mean and standard deviation of 16 years of data at REF. Negative values represent cumulative net CO_2 removal from the atmosphere while positive fluxes are cumulative net CO_2 addition to the atmosphere. The shading on each line is the 95% confidence bound around the mean value. Note that the graph begins on April 1st to more easily display and compare the snow-free season (April–November).

At the newly actively restored site (RES-1 year), CO_2 emission rates were initially similar to that of the unrestored sites (figure 1). Higher emissions during the first few years after active restoration have been linked to decomposition of the straw mulch layer, applied to maintain high humidity for the donor moss propagules (Waddington *et al* 2003). By the fourth year (RES-4 year), declining straw decomposition losses and productivity by the re-emerging vegetation layer had reduced the amount of CO_2 emitted annually (figure 1). The importance of restoring a shallow water table to the amount of CO_2 emitted annually is seen by the difference between the two RES-4 year lines (figure 1). A spatial gradient of restoration success was seen across the ~30 ha restored site, which was linked to a shallower water table (mean of 0.3 m versus 0.6 m) advancing revegetation and thus productivity in some sections relative to others (data not shown). At the older restored site (RES-15 year), CO_2 uptake similar to that of REF was observed after 14 years (Nugent *et al* 2018, figure 1). The CO_2 sink was linked to a sufficiently shallow water table, attributed to effective water retention by berms put in place during the restoration process (Nugent *et al* 2018).

The impact of after-use management of extracted peatlands on CH_4 emissions is primarily a function of the depth of the water table following rewetting. With a water table always below the surface, the unrestored sites released <1 g CH_4–C m^{-2} yr^{-1} (table S4); as such, a single value is given for the unrestored state in table 1. Very low CH_4 emissions were also observed during the initial years after restoration, before increasing in the third and fourth years to emissions similar to a decade and a half after restoration (table S4).

Net carbon loss from the peatland via DOC was greater at the unrestored sites and decreased substantially following restoration, to levels below that of REF (table S4) (Nugent *et al* 2018). We found no statistical differences (Student's *t*-test, $p > 0.05$) in net DOC export among the unrestored site ages as well as among the restored site ages (table S4) and, as such, a single value is given for the unrestored and restored states in table 1.

Comparison with IPCC Tier 1 emission factors

The unrestored chronosequence fluxes are broadly similar to the IPCC Tier 1 emission factors (EFs) for a drained temperate peatland (table 1). CO_2 emitted both on- and off-site are similar, although fixed IPCC Tier 1 values do not account for temporal trends in the GHG fluxes. Combining the IPCC Tier 1 CH_4 EFs using a ditch fractional cover of 0.05, representative of ditch density in Canadian extracted peatlands, results in a site-level mean of 2.5 g CH_4–C m^{-2} yr^{-1}, five times greater than the chronosequence value (0.5 g CH_4–C m^{-2} yr^{-1}) (table 1). This outcome becomes important when accumulated in the atmosphere over several years (see S4.1).

The CO_2 chronosequence captures the time needed after restoration to achieve a CO_2 sink, a period not explicitly included in the IPCC Tier 1 CO_2 EF (table 1). A transition period, as well as a temporarily larger CO_2 sink, after restoration is discussed by the IPCC, but, insufficient evidence was available to support the use of different default EFs; however, a transition period after restoration was highlighted as a primary reason to move toward Tier 2 methodology (IPCC 2014). Because of limited scientific literature, long-term studies in undrained peatlands were combined with observations at rewetted sites to calculate the default CO_2 EF (IPCC 2014). Notably, the CO_2 sink, once achieved in the chronosequence, is substantially larger than the IPCC Tier 1 value, while our restored DOC loss is less (table 1). Discharge was greatly reduced at the main study site (RES-15 year in figure 1) by ditch blocking and the creation of berms, which allowed the water table to rise significantly (McCarter and Price 2013). We hypothesize that the DOC flux will become more similar to undrained peatlands as water storage stabilizes with improved hydrological connectivity between the *Sphagnum* moss layer and the cutover peat.

The CH_4 chronosequence shows a gradual increase in emissions with time since restoration, while remaining at the lower end of the IPCC Tier 1 5%–95% confidence range (table 1). Observation sites included in the IPCC Tier 1 EF cover a range of water table positions, soil temperatures and prior land use, which can all influence the amount of CH_4 produced and emitted. Inclusion of sites that were slightly flooded during rewetting helps to explain the large confidence range (IPCC 2014). Maintaining a water table below the surface is a necessary step to mitigate CH_4 emissions (Strack *et al* 2014). Active restoration achieves this, with approximately 5 g CH_4–C m^{-2} less emitted annually at the Canadian sites compared to the average rewetting results contained in the IPCC (table 1).

Climate impact of peatland restoration

The Tier 2 active restoration scenario accumulates the atmospheric effects of fluxes during a 20 year unrestored phase and after restoration (figure 2), which follows the management history of the main study site. For a short period after restoration (in 2000 CE), the net radiative forcing (RF_{net}) continues to increase, reflecting the time needed for a restored site to transition to a carbon sink (figure 2(b)). A small increase in RF_{net} around 2030 reflects a decrease in the amount of carbon sequestered annually, back to the rate of an undrained peatland (REF in table 1). The radiative forcing switchover time (i.e. neutral climate impact) for this active restoration scenario is approximately 180 years (~2160 CE) (figure 2(b)). The Tier 2 immediate active restoration scenario shows a similar pattern, except that it circumvents the cumulative effects in the atmosphere of 20 years spent unrestored. Immediate active restoration achieves a radiative forcing switchover within roughly 25 years (~2005 CE) of extraction ceasing. Not restoring, on the other hand, results in a positive radiative forcing after 500 years that is seven times more powerful than the negative forcing achieved by active restoration. While both Tier 2 active restoration scenarios achieve a neutral climate impact, a Tier 1 average rewetting remains a positive radiative forcing, whether restored immediately or not (figure 2(b)). The climate cooling effect of on-site CO_2 removal from the atmosphere is virtually cancelled out by climate warming from off-site CO_2 emissions from DOC breakdown. Thus, the CH_4 perturbation, which has a relatively short effective lifetime in the atmosphere, is reflected in RF_{net} approximately leveling off after two decades (figure 2(b)). The uncertainty range of a Tier 1 average rewetting demonstrates that a net warming effect is much more likely than a net cooling effect (figure 2(a)). The climate warming from the Tier 1 no rewetting scenario is 12 times greater than a Tier 1 average rewetting and 1.3 times greater than the Tier 2 no restoration scenario after 500 years. Radiative forcing associated with emissions from actual peat removal during extraction is likely adding to the net climate impact. However, a complete lifecycle assessment of peat extraction actions is required to quantify these effects.

Radiative forcing is nW m^{-2} per hectare of peatland, relative to extraction termination in 1980 CE. In the Tier 1 scenarios, emission factors were treated as time-invariant atmospheric perturbations, while the Tier 2 scenarios used sustained, varying atmospheric perturbations interpolated from the chronosequence (table 1). Restoration occurs in 2000 CE in the Tier 1 average rewetting and Tier 2 active restoration scenarios, in 1980 CE in the immediate rewetting/restoration scenarios and does not occur in the no rewetting/restoration scenarios. The 500 year simulation confidence bounds are shown in (a) and the simulation average over the period 1980–2240 CE is shown in (b).

The climate benefit or cost of peatland restoration actions can be calculated by defining a reference and calculating the difference in net radiative forcing between the baseline (i.e. no restoration action) and alternative management action. Immediate active restoration reduces the climate cost by 83% at 20 years (table S5.1). In comparison, an immediate average rewetting results in a climate cost reduction of 26% at 20 years (table S5.1). Restoring immediately using an active restoration approach rather than the average

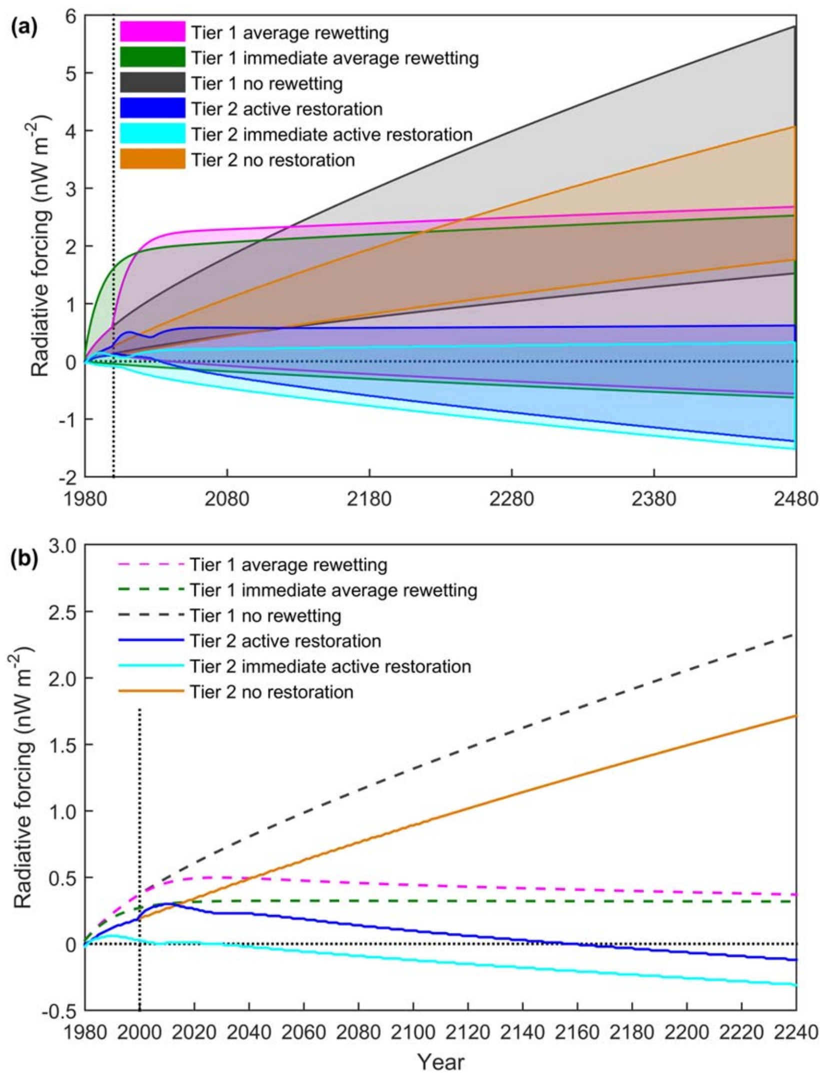

Figure 2. Instantaneous net (CO_2 + CH_4) radiative forcing of post-extraction peatlands.

rewetting approach reduces the climate cost of the peatland by 89% at 20 years (table S5.1). The choice of 20 years is used here for illustrative purposes only; prompt restoration has the highest net benefit during the first few decades.

Discussion

Our findings reveal that not restoring post-extraction peatlands leads to decades more CO_2 emissions to the atmosphere, directly and downstream, with low CH_4 emission. Restoring a CO_2 sink can take over a decade with active restoration, but once achieved, low on-site CH_4 emissions and low off-site CO_2 losses help maximize carbon sequestration, even exceeding undrained peatland carbon uptake rates.

It is socially and environmentally responsible to set a post-extraction site on a trajectory to become a healthy peatland (Joosten *et al* 2012). With successful restoration, the remaining carbon in the peat store is maintained and carbon sequestration sets the ecosystem on a course for eventual restoration of the lost peat—a process that may take thousands of years. Calculating the net ecosystem carbon balance by adding the carbon fluxes (CO_2 + CH_4 + DOC) reveals that an IPCC Tier 1 average rewetted peatland is a net source of 10 g C m^{-2} yr^{-1}. In comparison, an actively restored peatland is a net sink of 78 g C m^{-2} yr^{-1} after 15 years, with the likelihood of this sink being reduced to a net sink of 50 g C m^{-2} yr^{-1} by 30 years as fresher litter accumulates, the decomposition of which will contribute to greater CO_2 loss. Consequently, active restoration appears to allow the horticulture peat moss industry to realize a goal of sustainable management, although it is not renewable within the timeframe of this study.

We have shown that beyond making a choice to restore, using an active restoration technique within a short time frame is important to properly utilize peatland management as a climate change mitigation strategy. Restoration offers a climate benefit when applied immediately and with intent to restore the integrity of the ecosystem (figure 2). Active restoration accrues climate benefits once a site becomes an annual carbon sink, whereas IPCC Tier 1 average rewetting remains a positive radiative forcing over centuries. This case study illustrates that both timing of restoration and actions that result in favourable site conditions are important to actually achieve a sink. While this study demonstrates the radiative effects of a 20 year unrestored period, the Canadian industry average between the end of peat extraction and restoration is now closer to three years and thus the climate impact would be more similar to the immediate active restoration scenario. Horticultural peat moss companies could improve their climate impact by limiting the period of deep drainage during extraction to reduce CO_2 emissions and by managing sites being extracted so that CH_4 emissions are as low as or lower than undrained peatlands. The reduction in climate impact associated with active restoration of Canadian post-extraction peatlands is small in the global context, as the radiative forcing of anthropogenic-derived CO_2 is increasing at rate of almost 0.3 $W m^{-2}$ per decade (Myhre *et al* 2013). However, the extracted peatland area in Europe is large (Joosten 2009), and other peatland disturbances (e.g. petrol industry infrastructure impacts, forestry, agriculture, grazing, erosion, roads) would also benefit from prompt active restoration in improving the chances of C sequestration recovery and reducing the climate impact. Wide-scale peatland restoration, done appropriately, can be an effective long-term climate change mitigation strategy.

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Author contributions

All authors contributed to the discussion of the results and improvement of the manuscript. KAN contributed to the design of the study, analysed primary data for two of the eddy covariance sites, did model analysis and wrote the initial draft. IBS, NTR and MS co-conceived and designed the study. IBS and MS co-supervised KAN. SF and NTR designed the atmospheric perturbation model and contributed to the analysis of results. MH performed primary analysis on the eddy covariance data at two of the sites.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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