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Key Points:

- Radiocarbon age of DOC was analyzed for European and Asian peatlands
- Susceptibility to loss of old carbon after drainage varied by peatland type
- High-latitude peatlands are more resistant to old carbon loss

Supporting Information:

- Readme
- Figure S1
- Table S1
- Text S1

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Contrasting vulnerability of drained tropical and high-latitude peatlands to fluvial loss of stored carbon

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Abstract Carbon sequestration and storage in peatlands rely on consistently high water tables. Anthropogenic pressures including drainage, burning, land conversion for agriculture, timber, and biofuel production, cause loss of peat-forming vegetation and exposure of previously anaerobic peat to aerobic decomposition. This can shift peatlands from net CO_2 sinks to large CO_2 sources, releasing carbon held for millennia. Peatlands also export significant quantities of carbon via fluvial pathways, mainly as dissolved organic carbon (DOC). We analyzed radiocarbon (^{14}C) levels of DOC in drainage water from multiple peatlands in Europe and Southeast Asia, to infer differences in the age of carbon lost from intact and drained systems. In most cases, drainage led to increased release of older carbon from the peat profile but with marked differences related to peat type. Very low DOC-^{14}C levels in runoff from drained tropical peatlands indicate loss of very old (centuries to millennia) stored peat carbon. High-latitude peatlands appear more resilient to drainage; ^{14}C measurements from UK blanket bogs suggest that exported DOC remains young (<50 years) despite drainage. Boreal and temperate fens and raised bogs in Finland and the Czech Republic showed intermediate sensitivity. We attribute observed differences to physical and climatic differences between peatlands, in particular, hydraulic conductivity and temperature, as well as the extent of disturbance associated with drainage, notably land use changes in the tropics. Data from the UK Peak District, an area where air pollution and intensive land management have triggered *Sphagnum* loss and peat erosion, suggest that additional anthropogenic pressures may trigger fluvial loss of much older (>500 year) carbon in high-latitude systems. Rewetting at least partially offsets drainage effects on DOC age.

1. Introduction

Based on recent estimates, peats hold 470–620 Pg C globally, equivalent to 26–44% of estimated global soil C [*Page et al.*, 2011] or 59–78% of current atmospheric CO_2 [*Intergovernmental Panel on Climate Change (IPCC)*, 2007]. Of the total peat C stock, 81–85% is held in high-latitude (temperate, boreal, and subarctic) peats and 15–19% in tropical peats, mostly in Southeast Asia [*Page et al.*, 2011]. In many areas, peatlands have been heavily impacted by anthropogenic modification, notably drainage. In Europe (including European Russia), 26% of the peatland area has been converted to agriculture and 16% to forestry via drainage during the last century [*Joosten and Clarke*, 2002]. Tropical peatlands are subject to intensifying pressures, including deforestation and drainage for agriculture and biofuel production, primarily oil palm and pulpwood plantations [*Hooijer et al.*, 2010; *Mietinnen et al.*, 2012]. *Hooijer et al.* [2010] estimated that 47% of the total peat area in Southeast Asia had been deforested by 2006 and that 84% of this area had also been drained. Globally, *Joosten* [2010] estimated that 12% of all peatlands have been degraded. Since peat formation relies on the constraining effects of waterlogged, anaerobic conditions on decomposition, oxygen ingress following drainage can lead to dramatic increases in near-surface decomposition rates [*Limpens et al.*, 2008; *Freeman et al.*, 2001; *Couwenberg et al.*, 2010]. In Southeast Asian peatlands, the combination of accelerated aerobic decomposition and increased fire incidence during and after land clearance and drainage (a process also responsible for Asian “brown cloud” pollution events;

[*Page et al.*, 2002]) has led to estimated annual CO_2 emissions of 637–2255 Mt CO_2 yr^{-1}, equivalent to 2.3–8.2% of global CO_2 emissions from fossil fuel burning [*Hooijer et al.*, 2010]. Despite holding more C than the entire global forest area, peatlands have, until recently, received comparatively little attention under the UN Framework Convention on Climate Change.

As well as direct gaseous losses of CO_2 and CH_4, peatlands export carbon via runoff, primarily as dissolved organic carbon (DOC) and CO_2. DOC may be transported long distances downstream, whereas most fluvial CO_2 is rapidly lost to the atmosphere by evasion [*Billett and Harvey*, 2013]. These fluxes are often overlooked in terrestrial C budgets but may be quantitatively significant; for example, flux studies of aggrading high-latitude peatlands in Canada [*Roulet et al.*, 2007], Sweden [*Nilsson et al.*, 2008], the UK [*Dinsmore et al.*, 2010], and Ireland [*Koehler et al.*, 2011] suggest values in the range 13 to 26 g C m^{-2} yr^{-1}, compared to net ecosystem CO_2 exchange of -40 to -115 g C m^{-2} yr^{-1}. In tropical peatlands, DOC fluxes are typically larger, in the region of 50–60 g C m^{-2} yr^{-1} [*Alkhatib et al.*, 2007; *Baum et al.*, 2007; *Yule and Gomez*, 2009; *Moore et al.*, 2011, 2013]. Following peatland drainage, net CO_2 sequestration typically reduces or ceases, and in many cases the system becomes a large net CO_2 source [e.g. *Joosten and Clarke*, 2002; *Jauhiainen et al.*, 2012; *IPCC*, 2014], although some exceptions have been observed in high-latitude forestry-drained peatlands [e.g. *Lohila et al.*, 2011]. Simultaneously, measurements from a number of studies suggest that the DOC concentration and/or export flux also increases from both high-latitude peatlands [*Glatzel et al.*, 2003; *Wallage et al.*, 2006; *Strack et al.*, 2008; *Urbanová et al.*, 2011] and tropical peatlands [*Moore et al.*, 2013]. The fate of DOC within the fluvial system remains incompletely resolved, but a large proportion is considered likely to be returned to the atmosphere as CO_2 [e.g., *Cole et al.*, 2007; *Algesten et al.*, 2003; *Moody et al.*, 2013].

As well as uncertainties regarding the fate of DOC, there is uncertainty as to its source within the peatland ecosystem. One of the most effective tools to investigate this is radiocarbon (^{14}C). DOC derived from C stored deeper in the peat profile (which may be thousands of years old) is depleted in ^{14}C due to radioactive decay, whereas DOC derived from material photosynthesized within the last 50 years is elevated in ^{14}C due to ^{14}C-enrichment of atmospheric CO_2 by above-ground nuclear testing (so-called "bomb carbon"). Previous $DO^{14}C$ measurements from waters draining peat-dominated catchments in North America [*Schiff et al.*, 1997], Siberia [*Amon and Meon*, 2004; *Benner et al.*, 2004; *Raymond et al.*, 2007], and Europe [*Palmer et al.*, 2001; *Billett et al.*, 2007; *Evans et al.*, 2007; *Tipping et al.*, 2010] all show enrichment of DOC with bomb carbon, suggesting that the bulk of DOC leached from these systems is of recent origin, i.e., comprised of C fixed from the atmosphere within the last 1–10 years [*Tipping et al.*, 2010; *Raymond et al.*, 2007]. For intact peatlands, most of the DOC exported must therefore be derived from recently formed plant residues, rather than from older soil organic matter, implying that DOC does not represent a major loss pathway for long-term stored carbon [*Evans et al.*, 2007]. However, few studies have made $DO^{14}C$ measurements in waters draining drained or otherwise degraded peatlands. We hypothesized the following:

1. That artificial peatland drainage would, by exposing previously anaerobic peat to aerobic decomposition, lead to the release of old, ^{14}C-depleted DOC, indicating peat carbon loss (expanding the assessment of Asian peatlands undertaken by *Moore et al.* [2013]).
2. That this response would be common to boreal, temperate, and tropical peatlands.
3. That ^{14}C levels in rewetted peatlands would have returned to predrainage values.

To test these hypotheses we undertook a large-scale, comparative study of $DO^{14}C$ levels in samples collected from intact, drained, and (where present) rewetted peatlands from three countries in Europe (Finland, the United Kingdom, and Czech Republic) and two in Southeast Asia (Malaysia and Indonesia) where peat drainage has been widespread. The sites included represent both a broad latitudinal range (from 2°S to 63°N) and several major peatland types: boreal bog and fen, temperate raised bog, oceanic blanket bog, and tropical peat swamp. A number of other globally important peatland areas, notably the midcontinental peatlands of Western Siberia and North America, and the equatorial peatlands of Africa and South America, are not represented, although, in general, these areas have been less impacted by drainage [*Joosten*, 2010].

2. Methods

2.1. Site Descriptions

We collected a total of 46 samples for $DO^{14}C$ analysis, 33 from Europe and 13 from Southeast Asia (Table 1). Within each of the European countries studied, we collected samples from intact, drained, and rewetted peatland

Table 1. Location of Sampling Sites Included in the Study, With Summary Site Information[a]

Site Code	Site Name	Sampling Date	Latitude	Longitude	Peat Type	Vegetation	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)	Drainage Status	Ditch Spacing (m)	Ditch Depth (m)	Years Since Drainage (Restoration)
MY1	Cyberjaya, Selangor	6/23/2008	02°56′42″N	101°37′54″E	Tropical peat swamp	Forest	27.1	2312	Regional			
MY2	Cyberjaya, Selangor	6/23/2008	02°56′42″N	101°37′54″E	Tropical peat swamp	Forest	27.1	2312	Regional			
MY3	Banting, Selangor	6/25/2008	02°50′00″N	101°37′12″E	Tropical peat swamp	Oil palm	27.2	2259	Drained	70	0.9	11
MY4	Banting, Selangor	6/25/2008	02°50′00″N	101°37′24″E	Tropical peat swamp	Oil palm	27.2	2259	Drained	70	0.9	12
ID1	Sebangau	8/19/2008	02°19′07″S	113°54′38″E	Tropical peat swamp	Forest	26.7	2576	Undrained			
ID2	Sebangau	8/19/2008	02°18′57″S	113°54′19″E	Tropical peat swamp	Forest	26.7	2577	Undrained			
ID3	Sebangau	8/19/2008	02°18′42″S	113°54′01″E	Tropical peat swamp	Forest	26.7	2577	Undrained			
ID4	Kalampangan	8/21/2008	02°16′59″S	114°02′08″E	Tropical peat swamp	Cleared forest	26.7	2567	Drained	1000	5	13
ID5	Kalampangan	8/21/2008	02°21′10″S	114°00′07″E	Tropical peat swamp	Cleared forest	26.7	2559	Drained	1000	5	13
ID6	Kalampangan	8/21/2008	02°20′00″S	114°01′34″E	Tropical peat swamp	Cleared forest	26.7	2560	Drained	1000	5	13
ID7	Tumbangnusa	8/22/2008	02°21′53″S	114°07′42″E	Tropical peat swamp	Cleared forest	26.7	2539	Drained	1000	2.5	13
ID8	Tumbangnusa	8/22/2008	02°19′05″S	114°04′09″E	Tropical peat swamp	Cleared forest	26.7	2555	Drained	1000	2.5	13
ID9	Tumbangnusa	8/22/2008	02°17′48″S	114°05′55″E	Tropical peat swamp	Cleared forest	26.7	2556	Drained	1000	2.5	13
FI1	Lakkasuo	7/3/2009	61°47′32″N	24°18′45″E	Boreal raised bog	Seminatural bog	3.1	608	Undrained			
FI10	Valipuro	5/31/2008	63°52′42″N	28°38′58″E	Boreal raised bog	Seminatural bog	1.4	605	Undrained			
FI2	Keimolan Isosuo	9/7/2009	60°18′54″N	24°49′15″E	Boreal fen	Seminatural fen	4.8	649	Undrained			
FI3	Lakkasuo	7/3/2009	61°47′48″N	24°18′37″E	Boreal fen	Seminatural fen	3.1	608	Undrained			
FI4	Lakkasuo	7/3/2009	61°47′30″N	24°18′50″E	Boreal raised bog	Conifer forest	3.1	608	Drained	40	0.9	48
FI11	Suopuro	5/31/2008	63°52′45″N	28°39′14″E	Boreal raised bog	Conifer forest	1.3	607	Drained	40	0.9	26
FI5	Lettosuo	8/13/2009	60°38′20″N	23°58′50″E	Boreal fen	Conifer forest	4.3	612	Drained	40	0.9	*~35*
FI6	Lakkasuo	7/4/2009	61°47′50″N	24°18′43″E	Boreal fen	Conifer forest	3.1	608	Drained	30	1.1	48
FI7	Viheriäisenneva	7/5/2009	61°50′48″N	24°13′47″E	Boreal raised bog	Seminatural bog	2.9	606	Rewetted			54 (14)
FI8	Tervalamminsuo	8/13/2009	60°38′36″N	23°59′49″E	Boreal fen	Seminatural fen	4.2	616	Rewetted			*~35* (9)
FI9	Lakkasuo	7/4/2009	61°47′50″N	24°17′38″E	Boreal fen	Seminatural fen	3	611	Rewetted			54 (14)
UK 1	Conwy	9/23/2009	52°59′14″N	03°48′05″W	Temperate blanket bog	Seminatural bog	7.4	1292	Undrained			
UK 2	Forsinard	10/8/2009	58°22′27″N	03°58′09″W	Temperate blanket bog	Seminatural bog	7.1	884	Undrained			
UK 4	Conwy	9/23/2009	52°58′23″N	03°50′34″W	Temperate blanket bog	Seminatural bog	7.2	1346	Drained	15	0.5	*30*
UK 5	Forsinard	10/8/2009	58°26′19″N	03°55′57″W	Temperate blanket bog	Seminatural bog	7.4	849	Drained	35	0.5	*45*
UK 7	Conwy	9/23/2009	52°58′09″N	03°49′03″W	Temperate blanket bog	Seminatural bog	7.2	1345	Rewetted			*30* (1)
UK 8	Forsinard	10/8/2009	58°22′53″N	03°56′57″W	Temperate blanket bog	Seminatural bog	7.1	881	Rewetted			*45* (7)
UK 3	Bleaklow	6/7/2010	53°26′04″N	01°51′49″W	Temperate blanket bog	Degraded bog	7.3	1260	Undrained			
UK 6	Bleaklow	6/7/2010	53°26′31″N	01°50′08″W	Temperate blanket bog	Degraded bog	7.2	1252	Gullied	10[b]	2[b]	*100*
UK 10	Chew	3/15/2010	53°30′50″N	01°56′09″W	Temperate blanket bog	Degraded bog	7.3	1281	Gullied	20[b]	2[b]	*100*
UK 9	Bleaklow	6/7/2010	53°25′29″N	01°52′32″W	Temperate blanket bog	Degraded bog	7.4	1251	Rewetted			*100* (7)

Table 1. (continued)

Site Code	Site Name	Sampling Date	Latitude	Longitude	Peat Type	Vegetation	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)	Drainage Status	Ditch Spacing (m)	Ditch Depth (m)	Years Since Drainage (Restoration)
CZ1	Weitfaler bog A, Šumava	8/11/2009	49°01′01″N	13°25′01″E	Temperate raised bog	Seminatural bog	4.1	1176	Undrained			
CZ2	Blatenska slať, Šumava	8/11/2009	48°58′22″N	13°27′26″E	Temperate raised bog	Seminatural bog	3.3	1270	Undrained			
CZ9	Luzenská slať A, Šumava	11/3/2009	48°56′57″N	13°29′26″E	Temperate raised bog	Seminatural bog	3.7	1244	Undrained			
CZ3	Weitfaler bog B, Šumava	8/11/2009	49°01′01″N	13°25′01″E	Temperate raised bog	Dwarf pine forest	4.1	1176	Drained	15	2	*40*
CZ4	Ptačí slať, Šumava	8/11/2009	48°59′11″N	13°30′40″E	Temperate raised bog	Dwarf pine forest	4	1197	Drained	13	2	*40*
CZ8	Hraniční slať, Šumava	11/3/2009	48°56′49″N	13°29′10″E	Temperate raised bog	Dwarf pine forest	3.7	1244	Drained	15	2	*40*
CZ10	Buková slať, Ore Mtns	7/1/2010	50°22′18″N	12°45″21″E	Temperate raised bog	Seminatural bog	4.4	924	Drained	50	1	10
CZ11	Uhlišťe, Ore Mtns	7/1/2010	50°21′05″N	12°39′04″E	Temperate raised bog	Seminatural bog	4.9	872	Drained	30	0.7	10
CZ12	Velky Mocal, Ore Mtns	7/1/2010	50°23′39″N	12°39′10″E	Temperate raised bog	Seminatural bog	4.8	876	Drained	10	0.7	10
CZ5	Schachten, Šumava	8/11/2009	49°01′43″N	13°24′21″E	Temperate raised bog	Seminatural bog	3.9	1196	Rewetted			*40* (3)
CZ6	Březnická slať, Šumava	8/11/2009	48°57′49″N	13°28′51″E	Temperate raised bog	Seminatural bog	3.8	1228	Rewetted			*40* (3)
CZ7	Luzenská slať B, Šumava	11/3/2009	48°56 56″N	13°29′15″E	Temperate raised bog	Seminatural bog	3.7	1244	Rewetted			*40* (3)

[a] Sites are grouped according to country and by drainage status/condition within each country. Sites where the number of years since drainage is approximate are shown in italics. Dates are formatted as month/day/year.

[b] Drainage spacing and mean depth of gullied sites is approximate.

areas, with a minimum of three "replicate" sites per category. Where possible, intact, drained, and rewetted sites were colocated within the same peat unit. At each site, we recorded dominant vegetation cover, average ditch spacing, ditch depth, and date of drainage (in some cases only approximate dates could be obtained).

The Finnish sampling sites represented boreal mire systems, ranging from ombrotrophic (nutrient poor) bogs to minerotrophic (nutrient-rich) fens (see Table 1). Undrained and rewetted sites were typically dominated by *Sphagnum* and *Eriophorum* species (bog) or *Carex rostrata* (fen). Undrained sites contained some small trees (mainly *Pinus silvestris* and *Betula pubescens*), which became dominant at the drained sites and remained present in the rewetted sites. Data for two of the Finnish sites formed part of a study by *Billett et al*. [2012], which extended over the full snowmelt season; in this case we selected the final set of samples, collected under late spring low flow conditions on 31 May, as being most closely analogous to the data collected elsewhere. The Czech sites comprise small continental-raised bogs in the Šumava (Bohemian Forest) and Ore Mountains. Undrained sites are largely vegetated by *Sphagnum* species with some dwarf pine cover. Two sets of drained sites were sampled; the first set, in Šumava, were drained in the 1960s for forestry and now support some *Picea abies* plantation forest. Drains at these sites have not been actively maintained and are therefore partly infilled by vegetation. The second set, in the Ore Mountains, were drained in 2000. These sites, although surrounded by commercial forest, have not been planted and therefore retain their predrainage vegetation, with some expansion of dwarf conifer cover. Ditches at these sites remain fully open and active. Rewetted sites, also in Šumava, contain a mixture of *Sphagnum*, dwarf pine, and residual *Picea abies*.

UK sites were located in three regions. Two sets of samples were collected from adjacent areas of undrained, drained, and rewetted blanket bog from the Migneint, North Wales, and from the Flow Country, Northern Scotland. Vegetation at all sites was characterized by a mixture of *Sphagnum*, *Eriophorum vaginatum*, and dwarf shrubs (primarily *Calluna vulgaris*). A third set of samples were collected in the Peak District, Northern England, an area which has historically been affected by high levels of air pollution and intensive land use, which led to loss of *Sphagnum* cover, exposure of bare peat, and widespread gully erosion [*Tallis*, 1987]. Here samples were collected from one catchment-draining uneroded blanket bog, two catchments subject to gully erosion, and one in which erosion gullies have been blocked and active revegetation has taken place. All sites were dominated by *Eriophorum* species and dwarf shrubs.

Data collected from the tropical peatland sites included in this study have previously been reported as part of a DOC flux study by *Moore et al.* [2013] but are included here as part of the originally planned international ^{14}C data comparison. Nine samples were collected in Central Kalimantan, Indonesian Borneo, of which three were collected from near-intact peat swamp forest and six from a large area that was drained and deforested as part of the failed "Mega Rice Project" land conversion program in the late 1990s, and which has consequently been heavily impacted by forest fires. Three of these sites are considered heavily drained (ID4–6), and the other three moderately drained (ID 7–9) [*Moore et al.*, 2013]. The residual vegetation in this area is dominated by ferns, with a high proportion of exposed bare peat. A further four samples were collected in Peninsular Malaysia, south of Kuala Lumpur. Of these, one was collected from an active oil palm plantation and one from a nearby abandoned plantation site. A further two samples were collected from fragments of intact swamp forest; however. these sites were believed to be impacted by drainage and urban development in the surrounding areas and were not therefore considered to be representative of undrained peatland. Note that, due to the absence of substantial peat restoration activities in either of the Southeast Asian regions, no samples could be collected from rewetted sites.

To the best of our knowledge and from accompanying analyses showing similar base cation concentrations in samples from drained and undrained sites (T. Jones, personal communication, 2014), water flow paths remained within the peat mass (rather than underlying mineral soils) at all sites.

2.2. Sample Collection and Analysis

All samples were collected between 2008 and 2010, following consistent protocols. In Europe, all samples were collected during the growing season (one sample collected on 15 March, others from 31 May, latest sample on 3 November). To minimize potential flow-related variations in DO^{14}C, we aimed to sample under low to moderate flow conditions and, when possible, to sample groups of sites (i.e., undrained, drained, and rewetted sites) at each location on the same day (see Table 1). Southeast Asian samples were collected during the dry season (as the closest analogue to dry summer conditions at high-latitude sites) in late May (Peninsular Malaysia) and mid August (Kalimantan). The Kalimantan sites were subsequently resampled during the 2011 wet season ([*Moore et al.*, 2013], see discussion). In total we sampled 13 undrained sites, 18 drained sites (17 ditched and 1 gullied), and nine rewetted sites; sampling locations are shown in Figure 1. All samples were filtered in situ (Whatman GFF 0.7 μm glass fiber filters, prerinsed with sample) into prewashed polycarbonate bottles, returned to the UK and stored at ~2°C. DOC was determined using a Thermalox 5001.03 (Analytical Sciences Limited) total carbon analyzer following the nonpurgeable organic carbon method. Forty-two samples were analyzed for DOC-^{14}C at the Natural Environment Research Council's Radiocarbon Facility, East Kilbride. The remaining three samples (from Czech drained sites sampled in 2010) were analyzed at the Chrono Laboratory, Queen's University, Belfast.

Filtered water samples were acidified to pH 4 with 2 *M* hydrochloric acid and purged with helium to remove any inorganic carbon present, then neutralized to pH 7 with 1 *M* sodium hydroxide, rotary evaporated, frozen, and freeze dried. Weighed aliquots were combusted to CO_2 at 900°C in vacuum-sealed silica quartz tubes containing copper oxide and silver foil. The gas was converted to graphite by iron/zinc reduction, after which the ^{14}C content was determined by accelerator mass spectrometry at the Scottish Universities Environmental Research Centre, East Kilbride. The ^{14}C results were normalized to $\delta^{13}\text{C}{-}25‰$ and expressed as "% modern" (relative to a baseline of 100% modern in 1950). Dateable samples (those with $^{14}\text{C} < 100\%$ modern) were assigned ages in conventional radiocarbon years (BP; before present).

2.3. Data Analysis

Radiocarbon ages were initially analyzed following the conventional "carbon dating" approach of assigning a mean age to samples based on the decay rate of ^{14}C. This approach has been widely used in previous studies of DO^{14}C as well as for particulate organic carbon [e.g., *Raymond and Bauer*, 2001; *Benner et al.*, 2004; *Billett et al.*, 2007; *Evans et al.*, 2007] and provides useful indicative evidence as to whether samples were derived primarily from organic carbon photosynthesized since the onset of bomb testing in the 1950s or prior

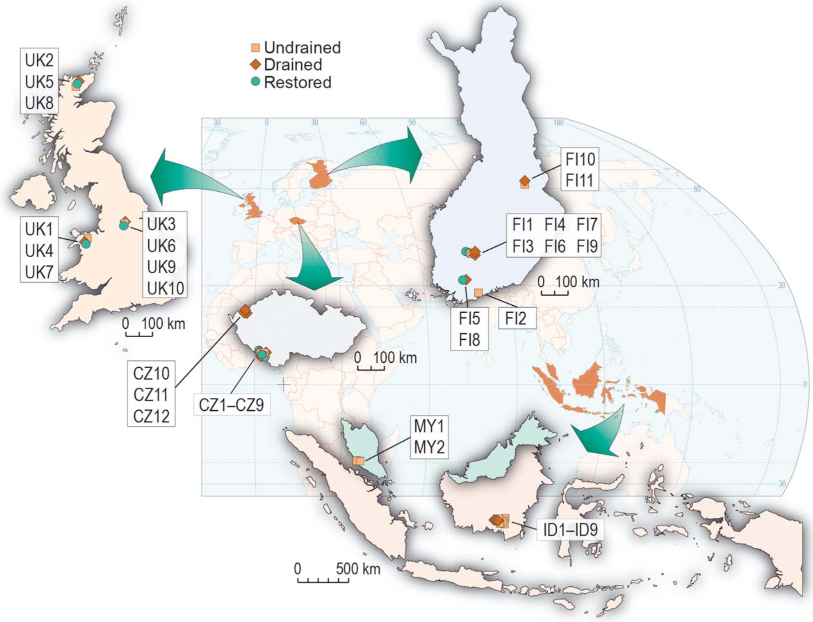

Figure 1. Location of sampling sites in the five countries included in the study (Site codes correspond to those listed in Table 1).

to this, in which case a "mean age" can be assigned. However, this approach has two important limitations. First, because atmospheric CO_2 had the same ^{14}C signature in years prior to and after the 1964 bomb peak (Figure 2, top), it is not possible to assign a unique age to any sample collected after the onset of bomb testing; therefore, all samples with $^{14}C > 100\%$ modern are simply termed "modern." Since this incorporates any material fixed from the atmosphere from 60 years ago up to the present day, it provides little insight into the sources or age of DOC from many undrained systems because, as noted above, most studies suggest that the majority of DOC in surface waters were derived from within this time period. *Evans et al*. [2007] noted that any samples with a ^{14}C value between 100% modern and the atmospheric $^{14}CO_2$ value at the time of sampling (104.6% modern in 2010) almost certainly contain a proportion of older, "prebomb" carbon, whereas samples with a ^{14}C value above current atmospheric $^{14}CO_2$ must contain a substantial proportion of "bomb" carbon.

A second issue with the assignment of a mean age value to DOC samples is that, in reality, they inevitably comprise material derived from a range of sources or depths, potentially spanning a broad age range. For a DOC sample with $^{14}C < 100\%$ modern, the conventionally assigned mean age effectively assumes that the sample contains no bomb-enriched carbon at all; therefore, if any bomb carbon is present, much of the remaining carbon must actually be older than the calculated mean age in order to compensate for this. Thus, the true mean age of a sample containing small amounts of bomb carbon will generally be greater than the conventional analysis would suggest.

To overcome some of these problems and to provide additional insight into the source and age of peat-derived DOC, we developed a simple age attribution model. This model (also summarized in the Supplementary Information of *Moore et al*. [2013]) relates proportional DOC production to peat depth, which in turn corresponds to carbon age. The model assumes that the greatest DOC production occurs at the peat surface, derived from carbon fixed via photosynthesis during the year of sampling, and that the amount of DOC production then declines exponentially with each subsequent year (i.e., down the peat profile). This model is conceptually consistent with a general understanding of the relationship between peat depth and decomposition rates [e.g., *Limpens et al*., 2008] and with observations of lateral hydraulic conductivity in peats, which indicate that lateral water movement can occur most rapidly near the surface, suggesting that more of the DOC flux will ordinarily be derived from near-surface layers [e.g., *Päivänen*, 1973; *Hoag and Price*, 1995; *Holden and Burt*, 2003]. A similar model was developed to interpret the $DO^{14}C$ signature of Arctic river samples by *Raymond et al*. [2007]. To permit a unique solution to their model, Raymond et al. assumed that all DOC present in their river samples, draining natural peatlands, were derived from post-1970 material, i.e., that it

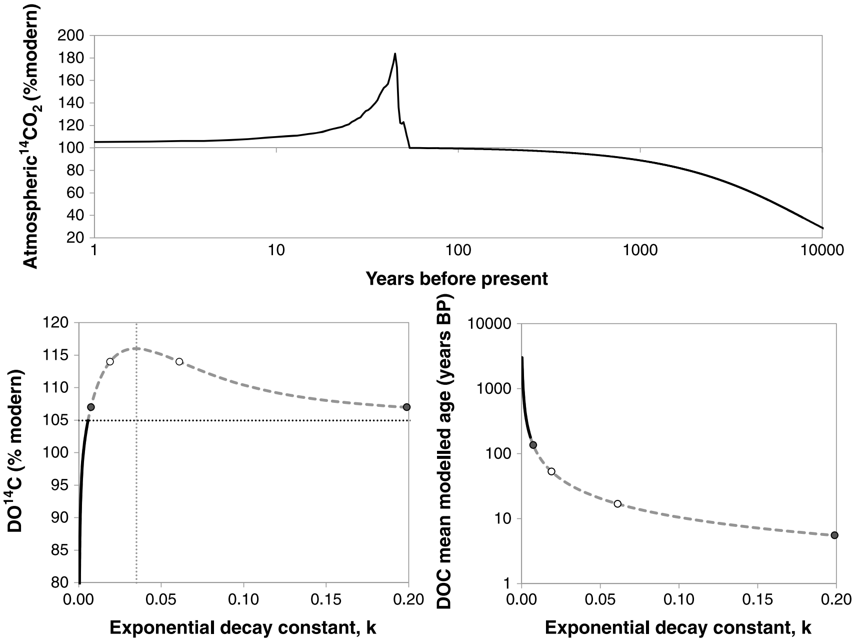

Figure 2. (top) Atmospheric $^{14}CO_2$ concentrations from 1 to 10,000 years B.P. (where "present day" for the study was 2009, time plotted on a log scale), and the relationship between (bottom left) $DO^{14}C$ value and (bottom right) mean-modeled DOC age and the decay constant, *k*, used in the exponential model of DOC release versus age (see section 2). The black part of the curve shows $DO^{14}C$ values for which a unique mean age can be derived ($DO^{14}C <$ present day $^{14}CO_2$, shown by the horizontal dotted line for a 2009 sampling year in Figure 2 (bottom left)). The dashed line indicates that part of the curve for which any given $DO^{14}C$ value can be produced by two possible solutions; the filled and open circles illustrate alternative solutions for two example values of 107% and 114% modern respectively. The two solutions converge at a peak "modelable" $DO^{14}C$ of 116.0% modern, shown by the vertical dotted line; note that any measurements above this value could not be reproduced by the model used.

had accumulated since the atmospheric $^{14}CO_2$ peak. In our study of drained peatlands, on the other hand, we anticipated that this assumption would not necessarily hold and that some samples were likely to contain pre-1970s or prebomb carbon. On this basis, the model was run over an extended time period, with a default length of 10,000 years, using a reconstructed sequence of atmospheric $^{14}CO_2$ concentrations. The model applied was as follows:

$$DO^{14}C = \sum_{t=1}^{t=10,000} \left({}^{14}CO_2 t \times \exp^{(-kt)} \right) \qquad (1)$$

Where $DO^{14}C$ is the measured ^{14}C level of the sample, *t* is the year prior to present day, $^{14}CO_2t$ is the ^{14}C level of atmospheric CO_2 in year *t* (assumed equal to the ^{14}C level in peat organic matter accumulated during that year), and *k* is an exponential decay constant with a value between 0 and 1. For each sample, the value of *k* was solved iteratively based on measured $DO^{14}C$ and the atmospheric $^{14}CO_2$ sequence shown in Figure 2 (top), using the Microsoft Excel Goal Seek numerical iteration function to match observed $DO^{14}C$.

Because the same atmospheric $^{14}CO_2$ levels occurred in years before and after the bomb peak, the exponential model used does not provide a unique solution in all cases. For samples collected in 2009, all samples with $DO^{14}C < 104.94\%$ modern (i.e., atmospheric $^{14}CO_2$ in that year), could be assigned a unique value of *k* (≤ 0.0056, indicating mean age >178 years). For samples with $DO^{14}C > 104.94\%$ modern, two solutions are possible (Figures 2 (bottom left) and 2 (bottom right)). These solutions diverge most strongly at $DO^{14}C$ values slightly above this threshold, which can be reproduced with a model based on either very recent carbon (high *k*) or a model with a lower *k*, implying a mean age on the order of 100 years. At higher $DO^{14}C$ values the two solutions converge toward a midrange age of 30 years. In the modeling study of *Raymond et al*. [2007], the authors made the assumption that, for their undrained peatland systems, the younger solution was more likely. This interpretation is also consistent with other previous studies of undrained high-latitude peatlands which have concluded that most of the DOC exported from undrained systems is of recent (<10 year) origin (see section 1). For our undrained sites, a similar inference seems probable; however, we recognize that the older solution remains possible. For drained or rewetted systems, either solution is plausible. In these cases, we did not favor one solution over the other *unless* a subset of the sampling sites within a given region had an unequivocally old ^{14}C signature (i.e., DO^{14}C $<$ 104.94% modern). In this case, if other sites within the same land use category had higher DO^{14}C values, we inferred that the older model solution was more probable for these sites. Again, however, we recognize that the alternate solution cannot be conclusively discounted.

For the Malaysian sites, we amended the age model to take account of the lower basal age of these coastal peatlands, which formed above coastal swamps between 3500 and 6000 years ago [e.g., *Wüst and Bustin*, 2004]. A maximum age of 6000 years was therefore assigned in the model. At the Borneo sites, some peat areas began to develop more than 20,000 years ago [e.g., *Page et al*., 2004], but cores show a hiatus in peat formation during the glacial period. This was followed by reinitiated peat formation and expansion of peat formation to new areas, following postglacial sea level rise around 10,000 years ago [*Page et al*., 2004; *Dommain et al*., 2014]. Therefore, we retained the default maximum age in the model for these sites.

For the drained Borneo sites, we refined our analysis (cf. that of *Moore et al*. [2013]) by accounting for the effects of peat fires known to have occurred since drainage in 1995, notably the major fires that took place during the 1997 El Niño year [*Page et al*., 2002]. Page et al. estimated that around 55% of the Mega Rice Project peat area burned to an average depth of 51 cm. Recent data (S. Page, personal communication, 2014) suggest total subsidence since 1995 now amounts to 110 cm for burnt heavily drained areas, 80 cm for burnt moderately drained areas, and 85 cm for unburnt heavily drained areas. Based on the available data we attributed 50% of this subsidence to combustion (assuming around half of each catchment was affected by burning), 25% to microbial oxidation, and 25% to compaction (i.e., assuming half of the subsidence in unburnt areas was due to oxidation and half to compaction). For the heavily drained catchments we estimated a mean subsidence of 1 m, and for the moderately drained catchments 70 cm (assuming the same ratio of subsidence for forested versus burnt areas as for the deep-drained areas). In a nearby intact peat core carbon dated by *Page et al*. [2004], the upper 90 cm was found to have a modern radiocarbon signature, with the shallowest dateable horizon, at 1 m depth, having a calibrated age of 140 years B.P. On this basis, we ran the age model for the heavily drained sites assuming that 75% of all peat above the 140 year B.P. layer (year class 198 in the model, for a 2008 sampling year) had been removed. For the moderately drained sites, we removed 75% of peat above 70 cm (equating to the year class 137 in the model based on the intact core). We recognize that there is considerable uncertainty surrounding these estimates, e.g., we did not have sufficient information to assign different burnt areas or burn depths to individual catchments. We also did not take account of possible fire effects elsewhere, although these are believed to have been small compared to the Borneo sites. The influence of these uncertainties is considered later.

Differences between samples (based on initial % modern values rather than derived ages) were analyzed using two-way analysis of variance (ANOVA), with drainage status (drained/undrained) and peat type (boreotemperate blanket bog, raised bog and fen, and tropical peat) as factors. Because the number of samples varied between regions and "treatments," the GenStat unbalanced ANOVA function was used (GenStat v13.1). An interaction term (drainage status × peat type) was included in the analysis. For the larger high-latitude data set, which included rewetted sites, a one-way unbalanced ANOVA was also carried out, with drainage status (undrained, rewetted, and drained) as the treatment factor. Two-sample *t* tests were used to test for significant differences between each pair of drainage classes within this data set.

Finally, to support the analysis of between-site differences in DO^{14}C (and in addition to the site attributes recorded in Table 1) we collated a data set of published estimates of the lateral hydraulic conductivity of different peat types. Due to the dependence of hydraulic conductivity on depth, we collated measured values from within a standard middepth range of 30 to 60 cm, for which the largest number of measurements were available. Study sites were classified as tropical peat, high-latitude fen, high-latitude raised bog, and high-latitude blanket bog, with between five and seven sites in each category. Further methodological information, data, and references are provided in the supporting information. Differences in mean middepth hydraulic conductivity were compared to the difference in mean measured DO^{14}C between undrained and drained sites for each of the four peatland categories.

Table 2. Measured Total Concentration, δ^{13}C, and ^{14}C Content of DOC at Each of the Sampling Sites, Together With Conventional and Modeled Radiocarbon Age Estimates[a]

					DOC Age (years Before sampling Date)		
Site Code	Drainage Status	DOC (mg L^{-1})	δ^{13}C (‰)	^{14}C (% modern)	Conventional	Modeled (High *k*)	Modeled (Low *k*)
MY1	Regional	4.0	−27.9	93.89	565	No solution	**745**
MY2	Regional	6.1	−28.5	88.97	997	No solution	**1164**
MY3	Drained	6.0	−27.2	67.28	3242	No solution	**3441**
MY4	Drained	13.3	−27.4	59.41	4241	No solution	**4374**
ID1	Undrained	60.1	−30	109.75	Modern	9	96
ID2	Undrained	62.5	−30.1	108.74	Modern	7	109
ID3	Undrained	63.5	−30.3	108.8	Modern	8	108
ID4	Drained	42	−29.8	98.86	150	No solution	**316**
ID5	Drained	35.6	−29.7	97.18	287	No solution	**406**
ID6	Drained	39.6	−29.6	97.07	297	No solution	**412**
ID7	Drained	62.6	−29	83.82	1475	No solution	**1616**
ID8	Drained	61.7	−29	85.49	1317	No solution	**1434**
ID9	Drained	62.8	−29.3	85.6	1307	No solution	**1422**
FI1	Undrained	18.8	−28.5	111.96	Modern	13	71
FI10	Undrained	29	−28.5	110.64	Modern	10	86
FI2	Undrained	94.6	−28.8	112.5	Modern	14	66
FI3	Undrained	13	−29.1	113.3	Modern	15	59
FI4	Drained	7	−28	106.52	Modern	*5*	145
FI11	Drained	17.5	−28.3	107.31	Modern	*5*	131
FI5	Drained	46.4	−28.1	103.88	Modern	No solution	**206**
FI6	Drained	11.3	−28	103.49	Modern	No solution	**218**
FI7	Rewetted	48.5	−28.2	109.33	Modern	9	101
FI8	Rewetted	81.1	−27.9	106.74	Modern	5	140
FI9	Rewetted	10.1	−28.7	112.51	Modern	14	66
UK 1	Undrained	19.2	−28.7	106.45	Modern	5	146
UK 2	Undrained	23.8	−28.4	109.22	Modern	9	102
UK 4	Drained	23.5	−28.5	111.43	Modern	12	77
UK 5	Drained	20.9	−28.3	106.57	Modern	5	144
UK 7	Rewetted	21.9	−28.2	111.66	Modern	12	74
UK 8	Rewetted	27.2	−28.3	106.71	Modern	5	141
UK 3	Undrained	61.8	−26.6	99.12	131	No solution	**399**
UK 6	Gullied	54.8	−26.5	95.11	463	No solution	**655**
UK 10	Gullied	10.3	−27.2	81.14	1738	No solution	**2006**
UK 9	Rewetted	34	−27.6	101.43	Modern	No solution	**291**
CZ1	Undrained	35.4	−27.4	113.98	Modern	17	53
CZ2	Undrained	35.7	−26.6	112.03	Modern	13	71
CZ9	Undrained	24.3	−27.4	112.11	Modern	13	70
CZ3	Drained	30.5	−27.2	114.46	Modern	18	49
CZ4	Drained	54.7	−27.4	111.94	Modern	13	72
CZ8	Drained	28	−28.3	111.67	Modern	12	74
CZ10	Drained	75.5	−28.1	109.36	Modern	9	99
CZ11	Drained	54.5	−28.2	102.18	Modern	No solution	**261**
CZ12	Drained	12.4	−25.7	101.33	Modern	No solution	**294**
CZ5	Rewetted	29.9	−28.1	111.75	Modern	13	74
CZ6	Rewetted	28.4	−27	108.44	Modern	8	113
CZ7	Rewetted	14.5	−27.9	110.1	Modern	10	91

[a] For details of age estimation model used, see section 2. Modeled mean ages for samples in which observed ^{14}C values could only be reproduced based on the 'low *k*' model (implying predominantly prebomb carbon content) are highlighted in bold.

3. Results

3.1. European Peatlands

Of the 34 samples collected from European peatlands, the conventional radiocarbon model indicated that DO^{14}C levels were modern in all samples other than three obtained from long-term degraded peatland sites in the UK Peak District (Table 2). DO^{14}C measurements are summarized by regional subgroup in Figure 3, and modeled DOC mean ages are summarized for the same groupings in Figure 4. Using the exponential model, however, DO^{14}C values from a further five samples could only be reproduced by a model with mean DOC age

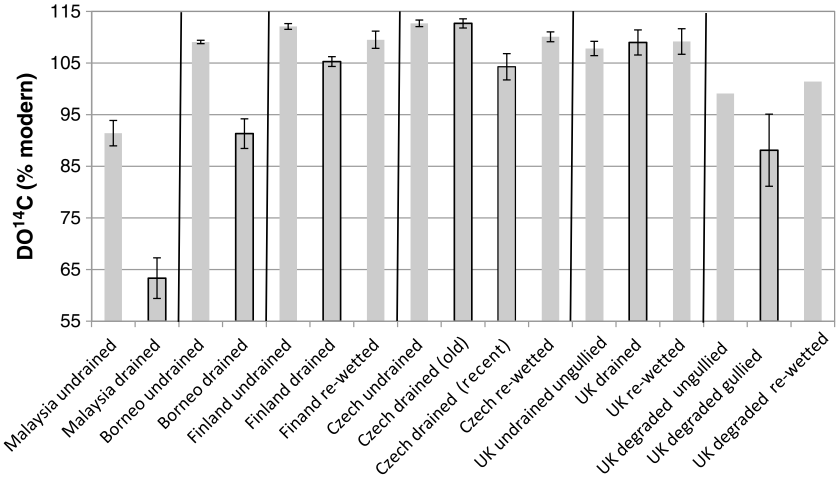

Figure 3. Mean radiocarbon (^{14}C) levels measured in DOC in runoff from undrained, drained, and rewetted peatlands in the six study regions. Error bars represent standard error of the mean (note only single samples obtained from two of the UK-degraded peatland classes). Bars representing drained peat classes are outlined.

exceeding 178 years. These samples were obtained from four drained sites in Finland or the Czech Republic, and from the remaining sampling site in the UK Peak District. Individual country results were as follows:

3.1.1. Finland

Results were broadly similar among the three and four sites within each drainage category. All undrained sites had DO^{14}C values in the range 110.6 to 113.3% modern, consistent with the interpretation that these intact peatlands export DOC with a largely young (≤15 years) radiocarbon signature. The alternate model solution for these sites would indicate a mean age of 59–71 years. For the drained sites, the observation that two sites had unequivocally older DO^{14}C values supports the inference that the remaining two sites, which had DO^{14}C slightly above current atmospheric $^{14}CO_2$, may be best explained by the older model fit, implying that the drained sites were exporting DOC with a mean age range of 131 to 218 years. For rewetted sites, measured DO^{14}C ranged from 106.8 to 112.5% modern, similar to the undrained sites. The two solutions for these sites imply a range of mean age from 5 to 14 years (young solution) or 66 to 140 years (old solution).

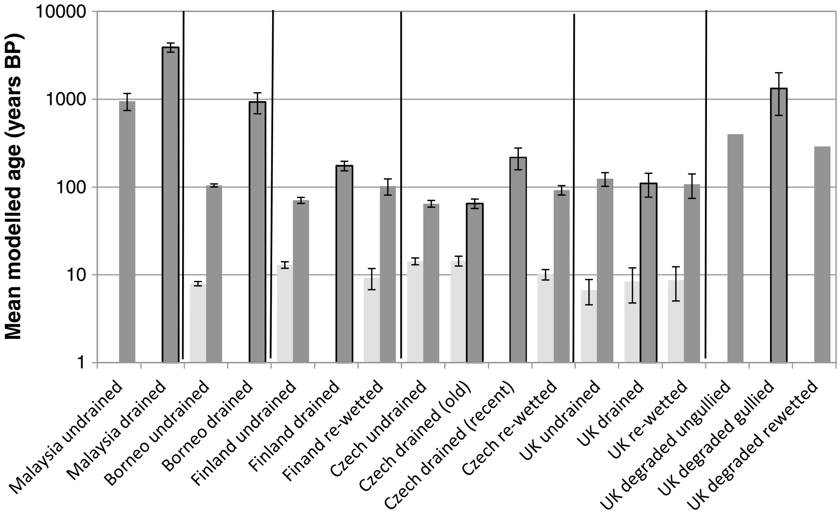

Figure 4. Mean DOC age modeled from observed DO^{14}C levels for undrained, drained, and rewetted sites in the six study regions. Regional subsets plotted as in Figure 2. Both age models are shown where two solutions were possible. Error bars represent standard error of the mean (note only single samples obtained from two of the UK-degraded peatland classes). Bars representing drained peat classes are outlined.

Table 3. Two-Way Analysis of Variance for DO^{14}C Versus Peat Type (Blanket Bog, Raised Bog, Fen, and Tropical)[a]

	Degrees of Freedom	Mean Square	*F*	*p*
Peat type	3	883	16.8	< 0.001
Drainage status	1	643	12.2	0.001
Drainage status × peat type	3	811	5.1	0.005
Residual	32	1688		

[a] Analysis undertaken using the GenStat unbalanced ANOVA function. Four sites affected by peat erosion (UK3, 6, 9, and 10) and two sites thought to be affected by regional water table drawdown (MY1 and 2) were excluded from the analysis. Table 3 shows ANOVA results.

3.1.2. Czech Republic

As for Finland, measured DO^{14}C among the undrained sites spanned a narrow range (112.1 to 114.0% modern), suggesting a recent origin (mean age 13 to 17 years) but with an alternative possible solution of 53 to 70 years. The two sets of drained sites sampled gave contrasting results. Samples collected from sites that were drained and afforested in the 1960s had DO^{14}C values similar to the undrained sites, whereas samples collected from recently drained and unforested sites had lower values, with two having conclusively old values. Modeled mean ages for these sites were 261 and 294 years. The three rewetted sites had DO^{14}C values in the range 108.4 to 111.8% modern, similar to (but slightly lower than) the undrained sites.

3.1.3. United Kingdom

Results from the UK sites contrasted strongly between the “intact” (undrained, drained, and rewetted) blanket bog sampling sites in North Wales and Northern Scotland, and the “degraded” (undrained, eroded, and rewetted) blanket bog sites in the English Peak District. These two groups are therefore considered separately. Samples from the intact areas showed a range of DO^{14}C values from 106.5 to 111.7% modern, with no clear differentiation according to drainage status. All of these samples could be explained by a “young” model fit to give mean DOC ages in the range 5 to 12 years.

The Peak District samples, as already noted, had very low DO^{14}C values (range 81.1 to 101.4% modern) suggesting mean DOC ages exceeding 290 years at all sites. Although only a single ungullied catchment was sampled, observed differences between this site (modeled mean age 399 years) and the two gullied catchments (mean age 655 and 2006 years) are consistent with the greater degree of water table drawdown in the latter [*Daniels et al.*, 2008]. The restored site had the lowest modeled mean age of 291 years.

3.2. Asian Peatlands

As noted earlier, most of the measurements from tropical Asian peatlands have been reported previously by *Moore et al.* [2013]. However, as described above, we refined the age model applied by *Moore et al.* [2013] in an attempt to account for the younger basal age of peat deposits in Malaysia and the effects of postdrainage fires in Borneo. Of the 13 samples collected, those from intact peat swamp forest in Borneo all had DO^{14}C in the range 108.7 to 109.8% modern. These observations are broadly similar to those from undrained European peatlands (Figure 4), and can be explained by a young model fit with a mean age range of 7 to 9 years. The drained and deforested Borneo peatlands all contained predominantly prebomb ^{14}C (83.8 to 98.9% modern), with modeled mean ages of 316 to 1616 years. Note that these modeled ages are 115 to 166 years greater than the “conventional” radiocarbon ages (Table 2). It is also worth noting that the pattern of results obtained from the Borneo sites, as reported here based on samples collected during the 2008 dry season, was closely reproduced by a second set of samples collected at the same locations during the 2011 wet season [*Moore et al.*, 2013].

For Peninsular Malaysia, all four samples collected contained predominantly prebomb ^{14}C. The two samples collected from residual areas of peat swamp forest had DO^{14}C values of 93.4 and 89.0% modern, giving mean-modeled ages of 746 and 1165 years, respectively. The samples collected from oil palm plantations had exceptionally low DO^{14}C values of 67.3 and 59.4% modern, giving mean-modeled ages of 3441 and 4374 years, respectively. As noted by *Moore et al.* [2013], the latter is believed to be the lowest soil-derived surface water DO^{14}C value recorded.

3.3. Interregional Analysis of DO^{14}C Data

For the interregional analysis of drainage effects, we analyzed DO^{14}C data from a total of 40 sampling sites across all five regions. Samples from the UK Peak District were omitted from this analysis, because the

Table 4. Two-Way Analysis of Variance for Drainage Status (Drained and Undrained)[a]

Parameter	Estimate	Standard Error of Estimate	Difference versus Reference	*t*(32)
Blanket bog-undrained	108.5	3.63		29.88
Raised bog-undrained	111.1	2.42	+2.6	0.6
Fen-undrained	111.3	3.63	+2.8	0.54
Tropical-undrained	109.1	4.19	+0.6	0.11
Blanket bog-drained	109.0	5.14	+0.5	0.08
Raised bog-drained	108.1	2.57	−3.5	−0.49
Fen-drained	103.7	5.14	−8.1	−0.91
Tropical-drained	84.3	2.57	−25.3	−3.16

[a] Analysis undertaken using the GenStat unbalanced ANOVA function. Four sites affected by peat erosion (UK3, 6, 9, and 10) and two sites thought to be affected by regional water table drawdown (MY1 and 2) were excluded from the analysis. Table 4 shows parameter estimates for each peat type/drainage category relative to an undrained blanket bog reference. “Undrained” sites include rewetted sites where present.

data suggest additional effects of other anthropogenic drivers (historic land use and atmospheric pollution) that have caused a loss of peat-forming vegetation independent of drainage status [*Tallis*, 1987]. Furthermore, the cause of water table drawdown (gully erosion) differs from the ditch drainage that has occurred elsewhere. The two samples collected from residual swamp forest areas in Peninsular Malaysia were also excluded, because these sites appeared to be influenced by the drainage of surrounding agricultural land and could not be confidently assigned to either the undrained or drained classes.

In a two-way ANOVA of the full data set, all rewetted sites were included in the “undrained” category. Results (Tables 3 and 4) indicate that both drainage status (undrained = 0, drained = 1) and peat type (blanket bog = 1, raised bog = 2, fen = 3, and tropical = 4) are highly significant ($p \leq 0.001$) predictors of DO^{14}C level. The interaction term is also highly significant ($p = 0.005$) with a large negative coefficient. As a result, while estimated DO^{14}C values for all four undrained peat classes are similar (between 108.5 and 111.3% modern), the estimated DO^{14}C values for drained sites decrease progressively from 109.0% modern in drained blanket bogs to 84.3% modern in tropical peats.

For the high-latitude European peatlands, we examined the influence of rewetting and drainage. A one-way ANOVA (undrained = 0, rewetted = 1, and drained = 2) indicated that drainage status had a significant effect on DO^{14}C ($p = 0.042$), with undrained sites having the highest mean value (111.4% modern) and drained sites the lowest (107.5% modern). Comparison of the individual drainage classes using *t* tests suggested that drained sites had significantly lower DO^{14}C than undrained sites ($p = 0.025$) but that rewetted sites were not significantly different to either undrained or drained sites ($p = 0.15$ and p = 0.21, respectively).

We found no relationship between measured DO^{14}C in drained sites and either ditch depth or ditch spacing (data not shown). There was also no consistent overall relationship between DO^{14}C in drained sites and either

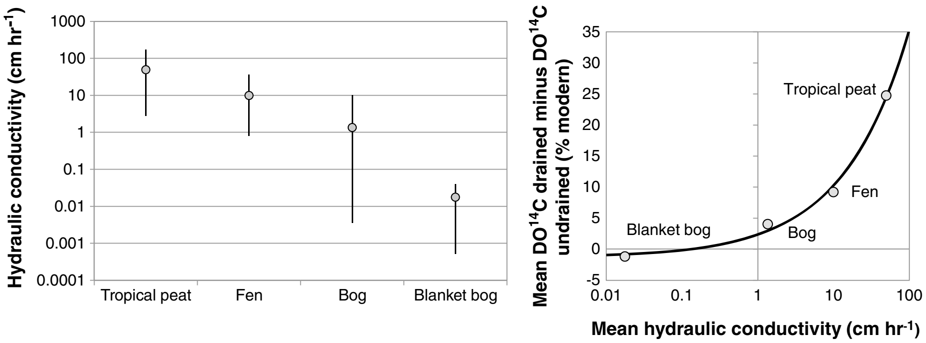

Figure 5. (left) Mean and range of middepth (30–60 cm) lateral hydraulic conductivity measurements reported for four peat categories, (right) the difference in mean measured DO^{14}C between samples collected from undrained and drained sites ($\Delta DO^{14}C_{drainage}$) within each of these four categories in our study, plotted against mean reported hydraulic conductivity for that category. For details on data sources of hydraulic conductivity values, see supporting information. Best fit line in Figure 5 (right) is based on a linear regression of $\Delta DO^{14}C_{drainage}$ against the square root of mean hydraulic conductivity (see equation (2)).

temperature or precipitation. Collated literature data on the lateral hydraulic conductivity at 30–60 cm depth (Figure 5 (left); see also the supporting information) show a high degree of variability in measured values within each of the four broad peat categories considered. However, the data also show a clear and substantial decline in hydraulic conductivity, by approximately 4 orders of magnitude, from tropical peats at one extreme to blanket bogs at the other. We compared these data to our results by calculating the mean difference in measured DO^{14}C between undrained and drained sites (ΔDO^{14}C$_{\text{drainage}}$, expressed as % modern) in each of the four peat categories (excluding the Pennine and undrained Malaysia sites, as above). While this analysis was limited by the number of sites in some categories (only two undrained and two drained sites in each of the fen and blanket bog categories, see Table 1), a relationship was observed between ΔDO^{14}C$_{\text{drainage}}$ and mean hydraulic conductivity across the four peat categories (Figure 5, right). This could be described by a square root relationship as follows:

$$\Delta \mathrm{DO}^{14}\mathrm{C}_{\text{drainage}} = 3.667\sqrt{\text{Hydraulic Conductivity}} - 1.305 \quad \left(R^2 = 0.993,\ p = 0.003\right) \tag{2}$$

4. Discussion

4.1. Sensitivity of Peatland DO^{14}C Leaching to Drainage

The DO^{14}C signatures of waters draining intact undrained peatlands in Europe and undrained peat swamp forests in Borneo are strikingly similar. They suggest that DOC leached from these systems is of predominantly recent atmospheric origin, and thus indicate a steady throughput of C from the atmosphere into plant biomass, part of which is then exported as DOC within a few years or (at most) decades. Since numerous other studies of intact temperate and boreal peatlands have made similar observations [e.g., *Schiff et al*., 1997; *Palmer et al*., 2001; *Evans et al*., 2007; *Billett et al*., 2007; *Raymond et al*., 2007], we consider that this represents a fundamental characteristic of intact, functioning peatlands, irrespective of peatland type. While this flux of modern DOC often represents a significant term in the overall peatland carbon balance [e.g., *Roulet et al*., 2007; *Dinsmore et al*., 2010; *Moore et al*., 2013] and should not therefore be overlooked in budget studies, a significant DOC flux is clearly not in itself symptomatic of net C loss, as has sometimes been suggested [e.g., *Bellamy et al*., 2005].

This stable situation, however, appears often to be altered by drainage and other (often associated) ecological disturbance. In both high-latitude and tropical peatlands, drainage can lead to the release of DOC with a lower ^{14}C content, which is most simply explained by an increased proportion of prebomb ^{14}C in runoff. This conclusion, which is consistent with our first hypothesis (that peat drainage would lead to release of old, ^{14}C-depleted peat carbon), is unequivocally demonstrated by DO^{14}C levels below current atmospheric ^{14}CO$_2$ values. This occurred at all the drained tropical sites studied and at four of the higher-latitude drained European sites. Since all sites were drained at least 10 years prior to sampling, it is likely that any increased contribution of prebomb ^{14}C results from decomposition of old peat carbon, rather than the flushing of a finite, preexisting ^{14}C-depleted DOC pool.

At the remaining European sites, the DO^{14}C results are more equivocal. For their drained and undrained catchment pair in Finland, *Billett et al*. [2012] tentatively ascribed lower DO^{14}C values in the drained catchment to a greater input of fresh DOC (i.e., material with a comparatively low ^{14}C value, close to the current atmospheric ^{14}CO$_2$ levels of around 105% modern). This was based on the assumption (as in *Raymond et al*. [2007]) that all DOC in runoff was derived from carbon fixed since the 1963 bomb ^{14}CO$_2$ peak. This interpretation is potentially consistent with long-term shifts in vegetation composition following drainage, notably an expansion of tree cover, which can alter the amount and degradability of litter inputs [e.g., *Straková et al*., 2012] and potentially to enhanced inputs of new, litter-derived DOC. Viewing their results in the context of the broader data set presented here, however, raises the possibility that generally lower DO^{14}C values in drained peatlands might instead be explained by a greater proportion of old carbon input from deeper within the peat profile. In particular, the observations from four drained sites in Finland and the Czech Republic of DO^{14}C levels below current atmospheric CO$_2$, which can only be explained by an input of older carbon, support this conclusion. However, it is clear that considerable variability exists between sites, and the extent to which lower (but still modern) DO^{14}C values can be explained by larger inputs of new litter-derived DOC versus old peat-derived DOC remains uncertain. The interpretation of DO^{14}C responses to drainage in some of the high-latitude regions must therefore remain somewhat tentative. Our results thus provide partial support for our second hypothesis (that DOC from drained boreal, temperate and tropical peatlands would show ^{14}C depletion) but with important caveats relating to the ambiguity of some results from temperate and boreal peatlands and to the apparent difference in sensitivity to drainage between peatland types. These issues are discussed below.

4.2. Relative Sensitivity of Different Peatland Types to Drainage

Differences in the DO^{14}C signatures of drained high-latitude and tropical peatlands sampled were pronounced. Although we identify a general tendency toward lower DO^{14}C levels in drained versus undrained peatlands, all drained high-latitude sites retained a modern conventional radiocarbon age (Table 2), and observed DO^{14}C at two thirds of these sites could be reproduced using two different age attribution models, giving a mean age of 49 to 145 years (low k model) or $<$20 years (high k model). Within the European data set, the evidence for drainage leading to mobilization of older carbon was strongest for the Finnish boreal mires, where all drained sites had a lower DO^{14}C than all undrained sites (mean difference of 6.8% modern, Table 2), with the lowest DO^{14}C values at the two drained fens. Data from the recently drained Czech sites show a similarly large reduction in DO^{14}C compared to the undrained sites, whereas data from sites drained in the 1960s–1970s did not differ from the undrained sites. It is possible either that the older drained sites have naturally rewetted (e.g., due to natural infilling of drainage ditches or to subsidence of the peat surface between the ditches) or that most of the soluble material from deeper within the peat column has already been lost during 40–50 years of exposure to oxygen. For the two UK blanket bog drained/undrained catchment pairs, we were unable to discern any consistent differences in DO^{14}C.

The response of tropical peatlands to drainage, in contrast, was dramatic. All eight actively drained sites were clearly exporting prebomb carbon in DOC, with modeled mean ages in the range 316–4400 years before the sampling date. Even the two sites in Peninsular Malaysia draining residual forest areas appeared to be affected by regional water table drawdown, with modeled mean ages of 745–1164 years. While we cannot exclude the possibility that seasonal or hydrologic factors may have influenced observed DO^{14}C values at the time of sampling (see below), these values are far lower than any recorded from undisturbed peatlands in either the tropics or high-latitude regions, regardless of hydrologic conditions. These data thus provide strong evidence for severe destabilization of tropical peatland carbon stocks following drainage and associated land use change [*Moore et al*., 2013] and further suggest that tropical peatlands may be inherently more susceptible to the release of old carbon in DOC compared to drained peatlands in other regions.

As noted above, variations in DO^{14}C among drained sites showed no clear relationship with either ditch spacing or ditch depth. However, it is likely that the actual intensity of drainage depends not only on the configuration of ditch networks but also on the physical properties of the peat itself. Our collated hydraulic conductivity data (Figure 5, left) highlight large differences in lateral hydraulic conductivity at 30–60 cm between peat types, from a mean of 48 cm h^{-1} in tropical peats to just 0.007 cm h^{-1} in blanket bogs. These differences are to a large degree consistent with the formation processes and resulting composition of different peat types. Tropical peats, formed under productive rainforest trees, rapidly accumulate poorly decomposed, fibrous peat containing a substantial proportion of tree remains [*Page et al*., 1999]. As well as having a high hydraulic conductivity near the surface, fibrous tropical peats retain a relatively high hydraulic conductivity at depth, and thus their overall transmissivity is also high [e.g., *Wösten et al*., 2008]. Continental mire systems are characterized by lower near-surface hydraulic conductivities and larger decreases with depth, but also show substantial differences according to peat type, with sedge-dominated fen peats having hydraulic conductivity values 2–3 times higher for any given degree of humification than *Sphagnum*-dominated bog peats [see supporting information Figure S1 and associated references]. In blanket bogs, the decrease in conductivity with depth is even more pronounced; *Hoag and Price* [1995] recorded hydraulic conductivities of around 330 cm h^{-1} at the surface of a blanket bog, but this declined by 5 orders of magnitude to just 0.004 cm h^{-1} below 50 cm depth. Thus, the overall transmissivity of the peat mass is very low, with most water movement occurring close to or over the peat surface, even in drained systems where water table drawdown may be limited to areas adjacent to or downslope of drainage ditches.

While we recognize a need for caution in comparing literature data (collected from different sites and using a range of methods) with DO^{14}C data collected from a limited number of sites and aggregated into just four categories, the strong apparent relationship between ΔDO^{14}C$_{\text{drainage}}$ and mean hydraulic conductivity by peat type (Figure 5, right) lends some support to the conclusion that differences in the hydraulic properties of different peatlands play a major role in determining their susceptibility to loss of old carbon via DOC (and by inference their overall sensitivity to carbon loss) following drainage. Although drainage itself has been shown to reduce hydraulic conductivity, due to the compaction of the peat [e.g., *Whittington and Price*, 2006], it seems unlikely that this would alter the relative differences in hydraulic conductivity between peat types. Based on these observations, we can tentatively infer that the sensitivity of peatland types to drainage is of the order of tropical peat > fen > raised bog > blanket bog.

It is worth noting that, in general, differences in hydraulic conductivity between peat types are reflected in the ditch spacings observed at the different study sites. In tropical peats, a single ditch or canal can drain areas extending over hundreds of meters [*Hooijer et al*., 2006], and ditch spacing is consequently high (e.g., typically 400 m in oil palm plantations). In a boreal fen with a relatively high hydraulic conductivity of 17 cm h^{-1}, *Hillman* [1992] found that a 50 m ditch spacing was sufficient to lower water table almost to the base of a network of 90 cm deep ditches. The Finnish sites had a similar ditch spacing (Table 1), although the depth of water table drawdown here is typically smaller. *Boelter* [1972] found that water tables were drawn down up to 50 m away from a ditch in a fibric North American peat but only within 5 m of a ditch in a nearby hemic peat. In UK blanket bogs, *Holden et al*. [2004] showed that water table drawdown only extended a few meters either side of drainage ditches, leading to the very high ditch densities (around 10–20 m) observed in many drained UK blanket bogs. Thus, it appears that the co-occurrence of lower observed $DO^{14}C$ with typically higher ditch spacings across our data set may arise because both are consequences of the contrasting hydrologic characteristics of the peat at different sites.

A further, obvious difference between tropical and high-latitude peatlands is their temperature; mean annual temperatures at the tropical peatland sites are around 20°C higher than the European study sites, so the increase in decomposition rates induced by an equivalent water table drawdown will be far greater. This effect is likely to reinforce the greater hydrologic sensitivity of tropical peats discussed above. Similarly, low rainfall rates in the boreal peats of Finland (especially compared to the blanket bogs of the UK) may make these systems more susceptible to any given depth and density of drainage.

4.3. The Effects of Rewetting

In the absence of measurements from tropical regions, we could only investigate the effects of peat rewetting in the European study areas. In all cases, $DO^{14}C$ in rewetted sites was above current atmospheric levels. Overall, observed $DO^{14}C$ levels at rewetted sites were intermediate between undrained and drained sites, but measured values were not significantly different to either undrained or drained sites. Differences between intact, drained, and rewetted sites were clearest in Finland, and a similar pattern was observed when comparing intact, recently drained, and rewetted sites in the Czech Republic. On the other hand, no clear differences were observed between older drained sites and rewetted sites in the Czech Republic, consistent with these sites having already naturally rewetted, as suggested above. No consistent differences in $DO^{14}C$ were recorded between the undrained, drained, or rewetted UK blanket bogs after the eroded Pennine sites were excluded. These results are broadly consistent with our third hypothesis, namely, that rewetted sites would have a modern $DO^{14}C$ similar to undrained sites, although the data from Finland suggest that this recovery in $DO^{14}C$ levels might not be complete in all cases.

4.4. The Influence of Site Disturbance and Vegetation Cover

Armstrong et al. [2010] observed a relationship between peatland vegetation type and DOC concentrations in UK blanket bogs, suggesting that the type (or absence) of vegetation at a site could also influence $DO^{14}C$. The degraded blanket bogs of the UK Peak District exhibit clear differences in their $DO^{14}C$ levels when compared to all the other European peatlands, with lower measured values at all four sample sites whether subject to water table drawdown (gullied sites) or not (undrained and restored sites). As noted above, this region was heavily affected by historic air pollution, combined with overintensive grazing and burning, which led to widespread loss of *Sphagnum* cover. This in turn led to degradation of the peat-forming acrotelm, exposure of large areas of bare peat, and the onset of gully erosion. While differences in modeled DOC age between the four Peak District sampling sites are consistent with the other study regions in showing release of older DOC from the catchment with the greatest water table drawdown, the consistently lower $DO^{14}C$ of all Peak District samples points strongly toward additional factors. The general reduction in vegetation cover across the Peak District sites may have contributed directly to a reduction in the supply of “new” DOC, observed in our study and in previous studies of undrained northern peatlands (see above). However, flux studies suggest that DOC fluxes are at least as high from the Peak District peats as they are from other, less degraded UK blanket bogs [*Billett et al*., 2010; *Pawson et al*., 2012], which implies that degradation of the vegetation (potentially augmented by burning of surface peat) has not simply reduced the supply of fresh DOC, but may, by triggering the loss of acrotelm peat, have exposed deeper, older carbon stores to accelerated loss as DOC. This interpretation is supported by evidence of a widespread surface recession and net C loss even from ungullied areas within the study region [*Evans and Lindsay*, 2010]. On this basis, we infer that degradation of peat-forming vegetation cover has led to a partial switch in DOC sources from recent plant material to deeper peat-derived carbon at all sample sites in this region, with water table drawdown at the gullied sites amplifying this effect, and leading to the very old (650–2000 year) estimates of $DO^{14}C$ age.

Elsewhere, disturbance of the peat ecosystem has largely occurred as an integral part of the drainage-related land use change. In the tropics, this has included forest removal, land-clearing fires and subsequent wildfires, and planting of new crops such as oil palm. While fires may directly remove near-surface peat via combustion, the removal of shading by deforestation can warm the peat surface by an additional 5°C, which would be expected to accelerate decomposition rates following drainage [*Hirano et al*., 2009] and thus also lead to enhanced release of older stored carbon as DOC. Drainage can also intensify near-surface warming by reducing the cooling effect of evaporation [*Hirano et al*., 2013]. These effects may be most severe in the degraded areas of the ex-Mega Rice Project from which the Borneo samples were collected, where vegetation is sparse and bare peat surfaces are exposed. At the Malaysian sites, the oil palm vegetation provides some surface shading, but nevertheless large areas of bare peat between trees are exposed to direct solar radiation, so similar effects seem likely. Conversely, at the Finnish and the older drained Czech sites, peat drainage was used to expand Norway spruce forest cover. This is likely to have an opposing, but smaller, effect; *Straková et al*. [2012] observed cooling in surface litter at a Finnish long-term forestry-drained peatland of around 0.5–1°C on an annual basis, increasing to 1–2°C in summer.

Overall, an index of site disturbance might help to explain observed variations in $DO^{14}C$ but would be difficult to objectively define based on available data across such a broad range of climate zones and ecosystems. In particular, it is difficult to entirely differentiate the direct effects of drainage (i.e., water table change) from linked disturbances leading to loss of peat-forming vegetation, exposure of bare peat or in extreme cases the loss of surface peat. In practice, these effects are likely to be reinforcing in most cases. As described above, we attempted to take account of surface peat removal via burning in Borneo, but found that the “removal” of a large amount of modern peat material from the model made rather little difference to the predicted ages (see below). Thus, the uncertainty relates less to the age estimates derived from the model and more to their interpretation; i.e., does the absence of modern carbon in DOC from drained tropical sites arise because modern carbon (in the form of plant exudates or recent litter decomposition) is no longer contributing to the DOC load, or because there is no modern carbon left available to leach, due to vegetation loss and fires? We note that some radiocarbon profile-dating studies have suggested the “truncation” of peat profiles in the ex-Mega Rice Project area, implying a loss of surface peat [*Dommain et al*., 2014] but are unaware of any radiocarbon measurements made directly below the peat surface that would enable us to constrain our interpretation further at this stage; such measurements would be helpful in future.

4.5. Limitations and Uncertainties

The collection of samples for radiocarbon analysis from 46 sites in five countries across Europe and Southeast Asia imposed some unavoidable constraints in terms of supporting data collection. This particularly affected the amount of consistent quantitative site information (such as water table, peat physical properties, and climate variables) we were able to collate across all sampling catchments and therefore our ability to explain differences in $DO^{14}C$ responses to drainage between sites and regions. Although some supporting information was collated from global data sets, the use and interpretation of these data carry a relatively high degree of uncertainty. An additional limitation of this study was the reliance on single water samples from each of the study sites. The amount, composition, and mean age of DOC are likely to vary seasonally and according to flow conditions at the time of sampling. While DOC concentrations in peatland drainage waters tend to vary less in response to flow than in mineral soil catchments [e.g., *Hinton et al*., 1997; *Hruška et al*., 2001; *Clark et al*., 2007], limited previous data from seminatural peatland catchments show that $DO^{14}C$ levels can vary between high and low flows [*Evans et al*., 2007; *Tipping et al*., 2010; *Billett et al*., 2012]. We attempted to minimize seasonal and hydrologic effects by (i) sampling paired sites on the same day, to minimize between-site variations in hydrology; (ii) sampling under lower flow conditions at all sites; and (iii) sampling during summer (Europe) or the dry season (Southeast Asia). While this strategy does not provide a representative annual value and cannot be used to interpret the effects of drainage on DOC flux, our intention was that this would allow us to identify the effects of drainage on the ^{14}C composition (and by inference source) of exported DOC, under conditions where drainage was likely to have its greatest impact. For the Borneo sampling sites, however, we were subsequently able to collect a second set of samples during the wet season and could therefore compare results for the different time periods. Measured wet season DO^{14}C values (reported in *Moore et al*. [2013]) were similar to the dry season observations included in this study and showed the same between-site contrasts, with values $>$108.7% modern in the undrained sites, and $<$98.9% modern at all drained sites. In contrast, apparent differences in DO^{14}C between the undrained and drained catchments in Northern Finland (sites FI10 and FI11, Table 2) were not evident when samples were collected during the preceding snowmelt period [*Billett et al*., 2012], suggesting that drainage-related differences may disappear here during wetter periods. This contrast appears consistent with the differences in drainage severity noted above, in particular, the lack of drainage effects observed in the high-rainfall intact UK blanket bogs, although further sampling would be required to elucidate this further.

For the Malaysian samples, we observed surprisingly low DOC concentrations ($\leq$14 mg L^{-1}, Table 2) when compared to other sites, notably those in Borneo where concentrations always exceeded 35 mg L^{-1}). While we cannot fully explain these low values, we note that the relatively young, shallow peats of Peninsular Malaysia developed directly over marine sediments and contain large amounts of reduced sulphur. Draining these soils causes sulphur oxidation and acidification, producing highly acidic drainage waters, and “acid sulphate” soils are consequently a significant land use problem in this region [e.g., *Paramananthan and Daud*, 1986]. Work in high-latitude systems has demonstrated that sulphur-induced acidification reduces DOC solubility and leaching from peats [*Evans et al*., 2012] and that sulphate oxidation in droughted peats can suppress DOC mobility via the same mechanism [*Clark et al*., 2006]. It is conceivable that a similar process could be operating in the dry season at the Malaysian sites. Chemical analysis of the samples collected for radiocarbon analysis (T. Jones, personal communication, 2014) showed that sulphate concentrations in the Malaysian samples were consistently higher than in samples from other regions and exceptionally high (100–200 mg SO_4 L^{-1}) in the two drained samples, which also had extremely low (3.1 to 4.1) measured pH values. Thus, it seems clear that drainage of the Malaysian peats has effectively triggered sulphuric acid leaching, which could provide a mechanism for suppressing DOC losses. We believe it is unlikely that this mechanism would influence the age of measured DOC. We conjecture that any DOC immobilized by high acidity levels during periods of water table drawdown might be remobilized and leached during wet periods, but again this will require further sampling to evaluate.

The age attribution model used is clearly also a source of uncertainty. As already discussed, higher DO^{14}C values can be reproduced in the model with two different k values. In addition, the assumption of an exponential decrease in DOC production versus peat depth (i.e., age) represents something of a simplification, since decomposition rates (and hence DOC production) may decline more rapidly across the boundary between the periodically aerobic acrotelm and the anaerobic catotelm. A more sophisticated model might allow for different k values within the different horizons but would be difficult to parameterize without multiple DO^{14}C measurements or other information from each site. Uneven peat accumulation rates or discontinuities in the peat stratigraphy might also affect the resulting DO^{14}C value, along with differences in maximum peat age at different sites. Reducing the basal peat age for the Malaysian sites had a negligible impact on age estimates for undrained sites, but slightly reduced mean-modeled ages for the drained sites (from 3780 to 3440 in MY3, and 4920 to 4370 in MY4). It is worth noting that the fitted model for these sites suggested that the amount of DOC exported actually *increases* with depth, rather than decreasing with depth as in all other sites, in order to reproduce such a low observed DO^{14}C value from the relatively young peat profile.

Incorporating removal of surface peat layers by fire at the drained Borneo sites had relatively little impact on the simulations (change in mean-modeled age $<$110 years in all cases) simply because the low observed DO^{14}C values indicate very little input of bomb ^{14}C-enriched material in either case. Perhaps counterintuitively, removing younger peat material from the model slightly reduced the mean-modeled age of the DOC because the reduced pool of bomb ^{14}C-enriched material allowed DO^{14}C observations to be reproduced by sourcing more of the DOC from shallower horizons within the remaining peat. While we recognize that there is considerable uncertainty in our parameterization of the horizontal and vertical extent of peat burning within each catchment, as well as peat profile age variation and peat heterogeneity more generally, we conclude that the basic inferences from the model are reasonably robust against different assumptions and local variations in the nature of the peat age profile. In summary, it is difficult to envisage a mechanism that would generate peat leachate DO^{14}C values below 104.9% modern other than the decomposition and/or mobilization of organic matter that has been stored in the peat for at least a century. Observed DO^{14}C values below this threshold in drained or otherwise degraded peatlands in tropical, temperate, and boreal regions, together with the consistent absence of such values from intact peatlands in any region, thus, provide strong evidence of the sensitivity of peat DOC loss to disturbances, particularly those associated with land use change.

At this stage, we consider that our data are insufficient to conclude whether observed shifts from "new" to "old" carbon as the source of DOC export from drained peatlands necessarily imply an increased overall DOC flux or an associated increase in peat decomposition. Since clear reductions in DO^{14}C were observed in sites drained many years (in some cases decades) previously, it seems highly unlikely that these results could be explained by the mobilization of finite pool of old DOC, as this would surely have been exhausted over these timescales. Furthermore, given that DOC concentrations were not consistently lower in drained sites (Table 2), we cannot explain an increase in observed DOC age via a reduction in new carbon inputs. This implies that decomposition rates of deep peat, as the source of old DOC, must have increased in response to drainage. This is consistent with broader understanding of the response of the peatland carbon cycle to drainage [e.g., *IPCC*, 2014]; however, it is important to note that the ^{14}C signature of DOC could theoretically change without an overall change in decomposition rate or total DOC export if the increase in decomposition of older, deeper peat was counterbalanced by a reduction in decomposition in shallower horizons and an accompanying reduction in the new DOC supply. Based on flux measurements reported by *Moore et al.* [2013], we can conclude that increased DOC age has coincided with increased DOC export at the Borneo sites, but without similar flux data we cannot determine whether this is the case at our other sites. However, a number of independent studies in temperate and boreal peatlands [e.g., *Glatzel et al.*, 2003; *Wallage et al.*, 2006; *Strack et al.*, 2008; *Urbanová et al.*, 2011; *Frank et al.*, 2014] suggest that DOC exports do increase following drainage, implying that older DO^{14}C values may well be indicative of increased overall carbon loss from the ecosystem. To elucidate this further, there is a need for additional DOC flux studies on (paired) drained and undrained sites, preferably in conjunction with further DO^{14}C and hydraulic conductivity profile measurements. This should support the development and application of robust models of hydrological and biogeochemical responses to drainage, leading to improved understanding of the sources, mechanisms, and carbon balance implications of DOC loss from drained peatlands.

4.6. Implications for Peatland Management

As reported in several previous studies, our results indicate that intact peatlands, within all countries and climate regions, export DOC that is derived largely from recent photosynthesis. This DOC is clearly a natural component of the peatland biogeochemical cycle and should be considered as such from a management perspective (even when, for example, high levels of DOC may be inconvenient from a water supply perspective). On the other hand, the general tendency within the data set for man-made drainage to increase the proportional contribution of old, peat-derived carbon to DOC export, clearly highlights the susceptibility of peatlands to anthropogenic disturbance and indicates that waterborne DOC export provides a potentially important ("cryptic") pathway of carbon loss and subsequent CO_2 emission from disturbed systems. Finally, our results suggest a gradient of peatland sensitivity to drainage, with tropical peat $>$ fen $>$ raised bog $>$ blanket bog. While additional measurements would help to confirm or refine these observations (for example, we collected few data from fen peats), the sequence appears consistent with published hydraulic conductivity data, with tropical peats having the highest values and blanket bogs the lowest. Higher peat surface temperatures, burning of surface peat, loss of natural vegetation cover, and other drainage-related disturbances also appear likely to be important exacerbating factors. While these results emphasize the general susceptibility of peatlands to drainage and other forms of anthropogenic degradation, they also highlight the apparently greater vulnerability of tropical peatlands. While the active drainage of northern peatlands is generally decreasing, and in some areas is now being reversed through rewetting and restoration, tropical peatlands remain under severe and ongoing pressure, particularly in Southeast Asia, as demands to drain and clear forest land for agriculture and large-scale plantations intensify. With relatively few studies having taken place in tropical compared to high-latitude peatlands, and a particular scarcity of comprehensive carbon balance studies, further measurements are needed to provide a more complete scientific understanding of peatland responses to anthropogenic disturbance and to support policy mechanisms designed to protect these ecosystems and the immense stores of carbon they contain.

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