Peat oxidation in an abandoned cutover peatland

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Waddington, J. M and McNeil, P. 2002. **Peat oxidation in an abandoned cutover peatland.** Can. J. Soil Sci. **82**: 279–286. Drained and cutover peatlands represent a persistent source of atmospheric CO_2. Contemporary, intermediate, and long-term rates of peat oxidation were measured in an abandoned cutover peatland to estimate the mass of C lost in order to determined if the oxidation rate has changed with time since abandonment. Contemporary rates were measured six times per week at 25 locations within the peatland using a portable infrared gas analyzer and an enclosure system. Mean daily peat oxidation was 7.7 g CO_2 m^{-2} d^{-1} or 4.8 mm yr^{-1}. Intermediate (2–13 yr) oxidation rates were estimated using dendrochronological techniques. Over 325 birch (*Betula* spp.) shrubs, an invasive group of species in abandoned cutover peatlands, were removed from the peatland after measuring the distance to the existing peat surface from the collar of the trunk. Dating the birches permitted the determination of the rate of peat oxidation and erosion since the establishment of individuals. Long-term oxidation (19 yr) was estimated with over 10 000 measurements on exposed stable tree stumps. The mean intermediate and long-term oxidation rates were 6.2 ± 2.9 mm yr^{-1} and 5.7 ± 1.1 mm yr^{-1}, respectively. These results suggest that peat oxidation rates remain high even after two decades of post-extraction abandonment. Since oxidation is an irreversible process, these results carry important implications for restoration work as well as for the determination of the long-term source of atmospheric CO_2.

Key words: Peatland, organic soil, oxidation, carbon dioxide, dendrochronology, peat extraction

Waddington, J. M. et McNeil, P. 2002. **Oxydation de la mousse de sphaigne dans les anciennes tourbières**. Can. J. Soil Sci. **82**: 279–286. Les tourbières exploitées et drainées libèrent constamment du CO_2 dans l'atmosphère. Les auteurs ont dosé le taux d'oxydation contemporain, intermédiaire et à long terme de la mousse de sphaigne dans une tourbière abandonnée en vue d'estimer la masse de carbone perdue et de déterminer si le taux d'oxydation se stabilise avec le temps. Le taux d'oxydation contemporain a été mesuré six fois par semaine à 25 endroits au moyen d'un analyseur de gaz à infrarouge et d'une enceinte. La moyenne quotidienne s'établit à 7,7 g de CO_2 par mètre carré et par jour, ou 4,8 mm par année. Le taux d'oxydation intermédiaire (2 à 13 ans) a été estimé par dendrochronologie. On a prélevé plus de 325 bouleaux (*Betula* sp.), espèce arbustive envahissante dans les tourbières laissées à l'abandon, après avoir mesuré la distance de la surface de la mousse au collet du tronc. L'âge de l'arbre a permis de déterminer le taux d'oxydation et l'érosion de la mousse de sphaigne depuis l'implantation des individus. L'oxydation à long terme (19 ans) a été évaluée à partir de plus de 10 000 relevés sur des souches d'arbre stables exposées. Les moyennes se situent à 6,2 ± 2,9 mm par année pour le taux d'oxydation intermédiaire et à 5,7± 1,1 mm par année pour le taux d'oxydation à long terme. Les résultats indiquent que le taux d'oxydation demeure élevé même après vingt ans d'abandon. L'oxydation étant un processus irréversible, de tels résultats sont lourds de conséquence pour ce qui est de la restauration du sol et de l'identification des sources libérant du dioxyde de carbone dans l'atmosphère à long terme.

Mots clés: Tourbière, sol organique, oxydation, dioxyde de carbone, dendrochronologie, extraction de la mousse de sphaigne

Natural peatlands are an important component of the global carbon cycle, storing ~23 g C m^{-2} yr^{-1} (Gorham 1991), but peatlands that are drained, cutover, and subsequently abandoned are a persistent source of atmospheric CO_2 (Nykänen et al. 1995; Silvola et al. 1996; Sundh et al. 2000; Waddington et al. 2002). Peatland drainage and extraction operations increase the depth of the aerobic zone, causing CO_2 emissions to increase 250 to 300% (Nykänen et al. 1995). However, peatland restoration and regeneration on these abandoned cutover peatlands can significantly reduce this CO_2 source (Waddington and Warner 2001) and can even return the peatland to a net carbon sink (Komulainen et al. 1999; Tuittila et al. 1999). The level of peatland restoration success, however, greatly depends on the degree of peat structural changes that occur post-abandonment due to peatland subsidence (Price and Schlotzhauer 1999). Peatland subsidence, which is the combination of peat compression, shrinkage, and oxidation leads to an increase in bulk density and a decrease in specific yield, which in turn alters water table position, volumetric moisture content and water tension (e.g., Bragg 1995; Price 1997). While peat compression and shrinkage are largely reversible during restoration re-wetting, peat oxidation is an irreversible process (Schothorst 1977). The change in oxidation rate with time since abandonment, therefore, has important implications for peatland restoration. Despite this, only a

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few contemporary (e.g., Sundh et al. 2000; Waddington et al. 2002) and long-term (e.g., Schothorst 1977) oxidation rate estimates have been made and, to our knowledge, no study has compared the contemporary and long-term oxidation rates within the same abandoned cutover peatland. The goal of this study, therefore, is to compare contemporary and long-term (19 yr) peat oxidation rates in an abandoned vacuum-extracted peatland in eastern Québec.

Schothorst (1977) studied the change in peat organic content of drained peatlands and determined that oxidation rates decreased with time in the first 6 yr since abandonment. Waddington et al. (2002) determined that peat substrate quality did not significantly decrease with time since abandonment in a Québec cutover peatland. Despite this, Waddington et al. (2001), using CO_2 exchange methods, determined that contemporary oxidation rates were greater in a 7- and 8-yr abandoned extracted peatland than in a 2- and 3-yr abandoned extracted peatland. Moreover, Prévost et al. (1997) found that the highest peat oxidation rates occurred during the third year post-drainage. No studies, however, have monitored the long-term (> 15 yr) change in oxidation rate during abandonment, in part due to the lack of suitable measurement techniques. Loss of organic matter approaches (e.g., Schothorst 1977) require knowledge of the initial organic matter content and bulk density of the peat once abandoned and gas exchange approaches (e.g., Waddington et al. 2002) are costly and would require annual measurements. Consequently, to date, the long-term (> 15 yr) total loss of C to the atmosphere during abandonment of cutover peatlands has also not been quantified.

During abandonment, the quantity of exposed wood on the surface of the peatland and the number of invasive species (e.g., birch, cattails, cottongrass) increase with time (e.g., Lavoie and Saint-Louis 1999). Some of this wood is raised to the peat surface through ice heaving, while other stable tree stumps become exposed due to the persistent removal of peat through oxidation. Birch (*Betula*) and other invasive species are able to colonize abandoned cutover peatlands due to the dry post-drained surface (Lavoie and Saint-Louis 1999). With time the birch roots also become exposed, again due to the persistent removal of peat through oxidation. The combination of exposed tree stumps and birch trees, which are not present in cutover peatlands prior to abandonment, can therefore provide a record of the total oxidation rate since abandonment. Such an approach can complement contemporary gas exchange techniques to compare total peat oxidation since abandonment.

The specific objectives of this paper are: (1) to determine the temporal an spatial variability in oxidation rates on abandoned cutover peatland through direct measurement of peat oxidation adjacent to exposed tree stumps and using dendrochronological techniques on the invasive birch trees, and (2) to compare those rates with contemporary oxidation rates (organic soil respiration) using net CO_2 exchange methods.

MATERIALS AND METHODS

This research was undertaken at the abandoned cutover section of the Bois-des-Bel peatland between May and October 1999. Net CO_2 exchange, peat temperature and water table position were measured two times per day every 2 d throughout the study period, whereas measurements of intermediate and long-term oxidation rates were made during the month of August.

Study Area

The Bois-des-Bel peatland is situated in the Bas-Saint-Laurent region of Québec (47°58′N, 69°25′W). The mean annual temperature is 3°C and the mean temperature for January and July are –12°C and 18°C, respectively (Environment Canada 1993). The mean annual precipitation is 924 mm. of which 27% falls as snow (Environment Canada 1993).

The Bois-des-Bel peatland is an ~200-ha treed bog of which 11.5 ha were vacuum extracted from 1973 until its abandonment in 1980. The vacuum extract area is divided into eleven 30-m × 300-m fields and separated by parallel drainage ditches that drain water south to the main drainage ditch (Fig. 1). CO_2 exchange measurements were undertaken in the 4th (western section of the peatland) and 10th (eastern section of peatland) fields. The 11 fields were also divided into twelve 30-m × 30-m plots. These plots were further divided into western, central, and easter sub-plots.

Since 1980, several invasive species (*Betula* spp., *Typha latifolia*, *Eriophorum vaginatum*) have colonized the abandoned peatland. Birch (*Betula* spp.) are present throughout the field and cattails (*Typha* spp.) have invaded the drainage ditches. Much exposed wood, covering ~15% of the surface area, exists in the Bois-de-Bel peatland. Some wood has been raised to the surface due to ice heaving while other tree stumps have become exposed due to the persistent removal of peat through oxidation and wind erosion.

Wood coverage is greatest in the southern end of the peatland (plots 1–4). A few bare patches occur around the meteorological site on field #4 as well as the northern end of fields 9 and 10 (plots 9 and 10) (Fig. 1).

Long-term Oxidation Rate Measurements

In the vacuum extraction method, existing stumps withing the peat are broken by the milling machinery to approximately ground-level, thus the exposure of these tree stumps above the present surface represents peat loss over the period since abandonment. The "long-term" (since 1980) oxidation rate was estimated, therefore, by measuring the distance between the tops of stable and exposed tree stumps to the current peat surface. to account for surface microtopography variability, four measurements (north, south, east and west sides of the stump) were made per tree stump. An average of 10 exposed stumps were measured in each sup-plot within the 11 fields. Measurements were made on a total of 3000 stable tree stumps. Peat deposition, due to wind erosion, was estimated by slicing the surface of the peat with a large knife and measuring the height of the loose aeolian peat above the peat surface. Peat wind erosion can be significant in abandoned vacuum-extracted peatlands, but Campbell et al. (2002) found that the subsidence of the Bois-des-Bel peat surface in 1998 and 1999 could not be linked to wind erosion. Indeed, Campbell et al. (2002) suggested that wind

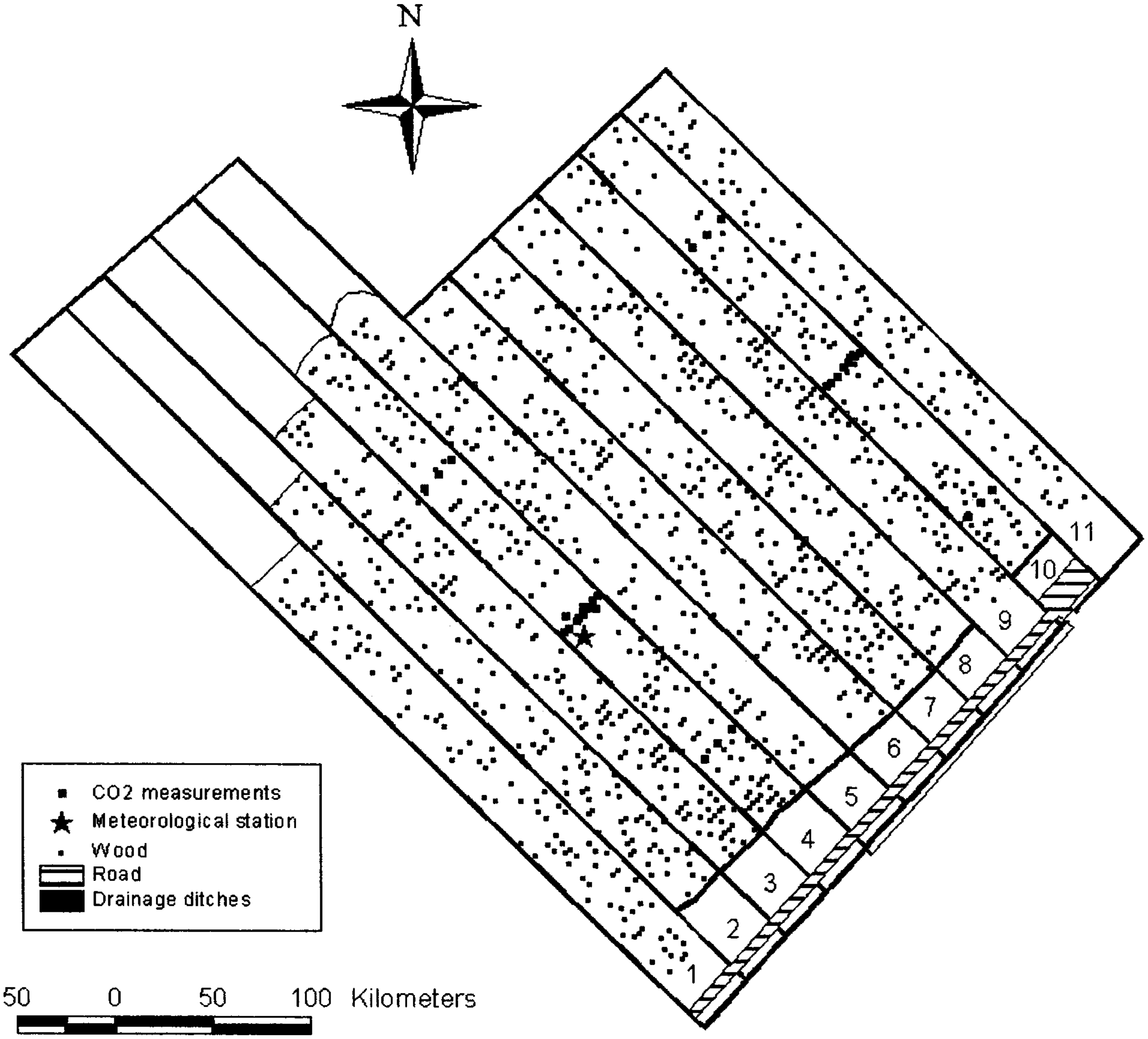

Fig. 1. Bois-des-Bel peatland illustrating the 11 peat fields (numbered), drainage ditches, location of CO_2 measurements (squares), meteorological station (star), and locations of wood (dots).

erosion was limited by relatively wet summer months and that the summer peat losses of 6.5 mm and 5.8 mm in 1998 and 1999, respectively, could be explained by oxidation. In this study we do not explicitly distinguish between long-term oxidation and erosion, but instead combine these two together. Given the results of the previous wind erosion study at this site (Campbell et al. 2002), we are confident that erosion is limited at Bois-des-Bel. Nevertheless, we obtained an estimate of long-term oxidation by taking the average of the four stump measurements, adding the depth of peat deposition, and dividing by 19 yr. In this approach we assume that all oxidation results in a lowering of the surface and that the tree stumps are "anchored" within the peat mass. This assumption implies that peat compression is not responsible for any of the surface lowering.

Intermediate Oxidation Rate (Dendrochronology) Measurements

To estimate the oxidation rate over the last 2 to 13 yr (intermediate term), the distance from the current peat surface to the collar of the trunk was measured on 329 birches (usually four birch samples within each 30-m × 30-m plot). Peat deposition was measured adjacent to the birch using the method previously described. A section of the birch trunk between the exposed roots and several centimeters above the collar was then removed form each birch sample and returned to the laboratory. In the laboratory, slices of the birch trunks were sanded with progressively finer grained sandpaper and the growth rings of each birch were counted using a microscope (Lavoie and Saint-Louis 1999). The intermediate oxidation rate was obtained by taking the birch collar to surface distance, adding the depth of peat deposition, and dividing by the age of the birch shrub.

Contemporary Oxidation and CO_2 Exchange Measurements

Measurements of soil respiration (R_{SOIL}) were made with a closed dynamic enclosure and PP systems EGM-2 infrared gas analyzer (IRGA) assembly placed and sealed over PVC collars set 10 cm into the peat at three locations (upper, middle and lower) in each of the 4th and 10th fields (Fig. 1) The upper, middle, and lower locations were ~ 50, 150, and 250 m north of the southern main ditch. At each location, collars were placed 5 m from each ditch and in the centre of the field. R_{SOIL} was measured using an opaque static enclosure. The enclosures covered a surface area of 0.05 m^2 with a volume of 10 L. CO_2 concentrations were measured for a 4-min duration at 1-min intervals and flux was calculated as a linear regression between concentration and time. Fans inside each enclosure ensured well-mixed air during the sampling period. Because of a diurnal variation in CO_2 flux (see Petrone et al. 2001), CO_2 measurements were made two times per day every 2 d. The mean daily flux was determined using a linear interpolation between individual measurement dates. Coincident with CO_2 measurements, peat temperature was measured adjacent to the enclosure at 2-, 5-, and 10-cm depths using thermocouples. Peat temperature at the meteorological station (Fig. 1) was measured using thermocouples at depths of 2, 5, 10, 15, 20, 35, 50, and 75-cm and logged half hourly on a CR10X datalogger.

RESULTS

Long-term Oxidation Rate Estimation

Mean long-term oxidation rate and total deposition at Bois-des-Bel peatland were 5.7 ± 1.1 mm yr^{-1} and 1.1 ± 0.8 cm, respectively. The maximum and minimum long-term oxidation rates were 10.7 and 2.7 mm yr^{-1}, respectively, while total deposition ranged from 0 to 3.8 cm.

There were no significant differences ($P < 0.05$) in long-term oxidation rate and deposition between plots within the same field. There were, however, several differences in long-term oxidation rate and deposition between the fields (Fig. 2). The easternmost field (field no. 11), for example, had the greatest amount of deposition (2.5 ± 0.6 cm, Fig. 2a) and the lowest long-term oxidation rate (5.0 ± 0.8 mm yr^{-1}, Fig. 2b). The adjacent field to the west (field no. 10) had the highest mean long-term oxidation rate (6.6 ± 1.2 mm yr^{-1} of all fields, especially in the central portion of the field. The central fields (fields no. 4, no. 7, and no. 8) within the Bois-des-Bel peatland had the lowest deposition (0.4 ± 0.4 cm). The lowest long-term oxidation occurred at the eastern and western edges (fields no. 1 and no. 11, respectively) (Fig. 2).

Because of these differences in long-term oxidation rates between fields, detailed analysis of the spatial variation in long-term oxidation rates on the same fields (fields no. 4 and no. 10) in which the contemporary measurements were made was necessary. Long-term oxidation rates in field no. 4 ranged from 4.2 to 8.6 mm yr^{-1}, from 3.5 to 7.7 mm yr^{-1}, and from 2.9 to 6.5 mm yr^{-1} in the eastern, central and western sections of the field, respectively. Similar variability existed in field no. 10 with long-term oxidation rates ranging from 3.4 to 7.9 mm yr^{-1}, from 4.9 to 8.2 mm yr^{-1}, and from 5.1 to 8.2 mm yr^{-1} in the eastern, central and western sections of the field, respectively. There was no significant difference ($P < 0.05$) in long-term oxidation rates between the western, central and eastern sections of the field (Table 1). Mean long-term oxidation rates of fields no. 4 and no. 10 were 5.9 ± 1.3 and 6.6 ± 1.2 mm yr^{-1}, respectively. Mean deposition in field no. 4 (0.2 ± 0.1 cm) was significantly lower and only 13% of that in field no. 10 (1.5 ± 1.0 cm) (Table 1). Deposition ranged from 0.1 to 0.3 in the east and from 0.0 to 0.5 cm in the central and western sections of field no. 4. Field no. 10 deposition ranged from 0.5 to 3.2, from 0.3 to 3.7, and from 0.6 to 3.8 in the eastern, central and western sections of the field, respectively.

Intermediate Oxidation Rate Estimation

The intermediate oxidation rate, as determined from the birch trees, is 6.2 ± 2.9 mm yr^{-1}. The birch shrubs ranged from 2 to 13 yr old, with a mean age of 6.0 ± 1.5 yr. The distance between the present peat surface and the birch collar ranged from 0.3 to 9.4 cm with a mean of 3.6 ± 1.6 cm. The mean oxidation rate was calculated for each age group (plotted as year of birch initiation) of birch shrubs (Fig. 3). Oxidation rates decrease with increasing birch age ($r^2 = 0.80$). The oxidation rate around 2-yr old birch shrubs was 12.3 ± 1.1 mm yr^{-1} while the oxidation rate around 13-yr old specimens was ~4 times lower at 3.0 ± 0.7 mm yr^{-1}. Mean oxidation near 5-yr old birches was 6.6 ± 3.0 mm yr^{-1}, whereas it was 5.4 ± 2.3 mm yr^{-1} adjacent to 7-yr old shrubs.

Contemporary Oxidation Rate Estimation

R_{SOIL} was 5.1 ± 5.2 g CO_2 m^{-2} d^{-1} and 6.9 ± 6.6 g CO_2 m^{-2} d^{-1} for the middle section of field no. 4 and field no. 10, respectively. Given the mean peat bulk density at field no. 4 (0.12 ± 0.02 g cm^{-3}) and field no. 10 (0.15 ± 0.03 g cm^{-3}), this respiration rate translates into a contemporary oxidation rate of 4.0 ± 4.0 mm yr^{-1} and 4.3 ± 4.1 mm yr^{-1} for fields no. 4 and no. 10, respectively. Overall contemporary oxidation including measurements from the upper, middle, and lower transects on both fields was 7.7 g CO_2 m^{-2} d^{-1} or 4.8 mm yr^{-1}. Unlike the long-term oxidation estimates, there was considerable variability in contemporary oxidation rates within plots and plot sections (Table 2). For example, soil respiration was 10 to 50% greater in the western and eastern sections than the central location (Table 2). Moreover, fluxes were greater in the southern plots of a field than in the middle and northern plots (data not shown). While contemporary oxidation rates exhibited higher rates on the edges of a field (3.9 and 4.8 mm yr^{-1} at field no. 4) than in the central section (3.2 mm yr^{-1} at field no. 4), they were not significantly different (Table 2).

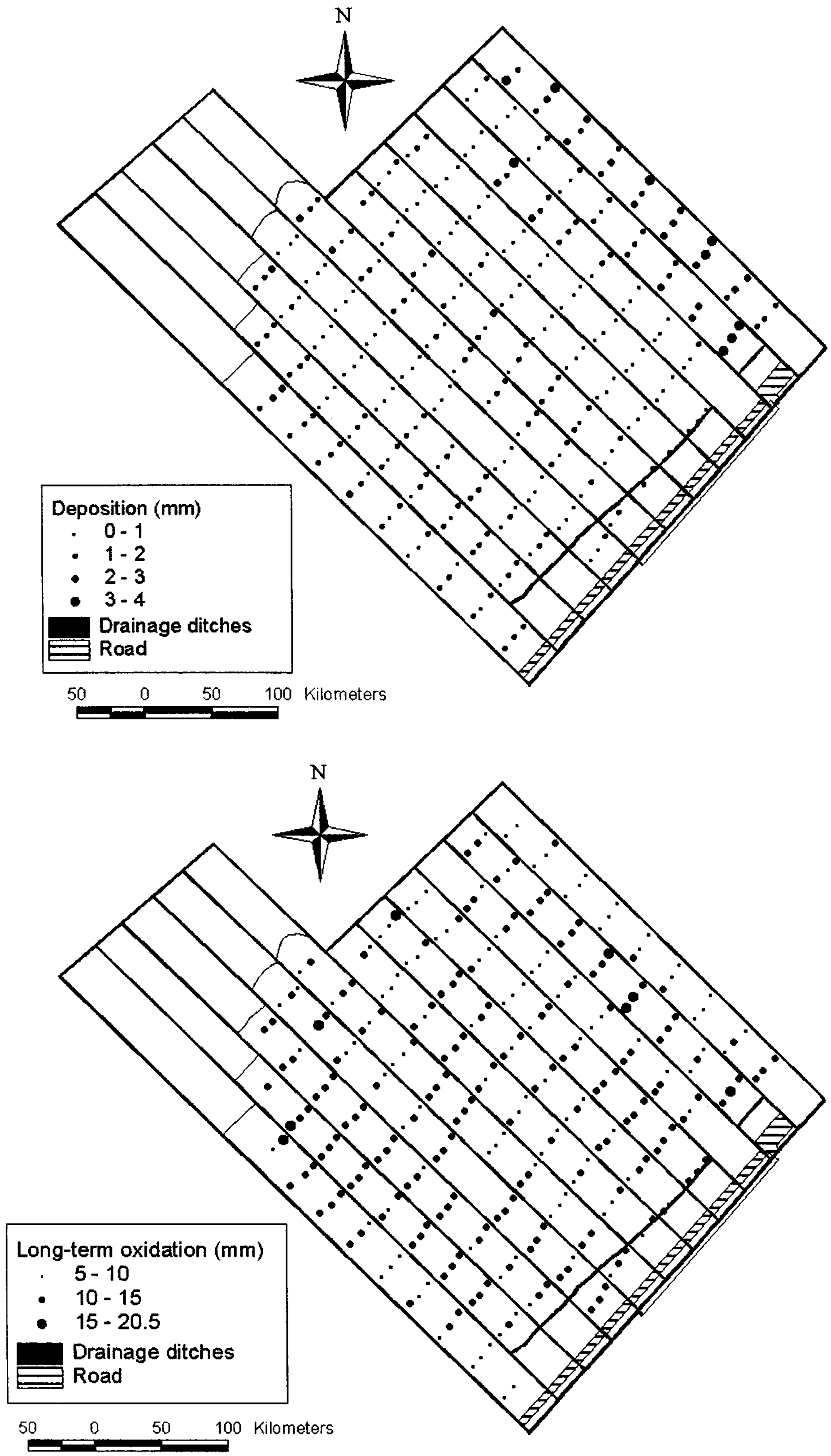

Fig. 2. Spatial variability in (a) deposition rate, and (b) long-term oxidation rate.

Table 1. Long-term oxidation rate (mm yr^{-1}) and total deposition (mm) for the western, central and eastern sections of field no. 4 and field no. 10. Values in parentheses represent one standard deviation

Field	Location	Oxidation rate (mm yr^{-1})	Total deposition (mm)
4	West	5.28 (1.15)	0.24 (0.14)
4	Centre	6.23 (1.50)	0.15 (0.18)
4	East	6.30 (1.28)	0.19 (0.08)
10	West	6.82 (1.07)	1.57 (1.05)
10	Centre	6.82 (1.10)	1.34 (1.17)
10	East	6.09 (1.38)	1.51 (0.78)

Mean water table position at western, central, and eastern sections was –55.9, –55.2, and –54.0 cm at field no. 4 and –48.6, –53.7, and –49.0 cm at field no.10, respectively. Mean –10 cm peat temperature at western, central, and eastern sections was 10.1, 12.6, and 11.7°C at field no. 4 and 8.3, 11.0, and 8.3°C at field no. 10, respectively.

DISCUSSION

The intermediate birch tree (6.2 ± 2.9 mm yr^{-1}) and long-term tree stump (5.7 ± 1.1 mm yr^{-1}) oxidation rates were similar and both were higher than the contemporary net CO_2 exchange (4.8 ± 6.6 mm yr^{-1}) oxidation rate. The net CO_2 exchange approach, however, does not incorporate peat loss due to wind or water erosion. Furthermore, the contemporary approach accounts only for oxidation during the growing season and is therefore likely underestimated. Moreover, with the tree stump and birch tree methods, we have also assumed that all peat oxidation (shallow and deep) results in a lowering of the peat surface. Consequently, a comparison of the absolute difference in peat loss due to oxidation only (exclusive of peat erosion) is not possible. Campbell et al. (2002) suggest that while the peat surface did drop at Bois-des-Bel, the absence of sudden elevation changes points to oxidation rather than wind erosion, which, to a certain extent, verifies our assumption. Considering that the net CO_2 exchange method is likely a conservative estimate, all three approaches indicate a peat oxidation rate of approximately 6 mm yr^{-1}.

Temporal Variability in Oxidation Rate

The long-term (19 yr) oxidation rate at the Bois-des-Bel peatland is 18% greater than the contemporary oxidation rate but 9% less than the intermediate oxidation rate. This suggests that the oxidation rate at Bois-des-Bel has persisted over time and perhaps even increased, given the conservative contemporary estimate.

The large within-year variability in intermediate oxidation rate is similar to the contemporary variability in net CO_2 exchange and likely reflects microsite differences in peat quality, volumetric moisture content, and temperature (Waddington et al. 2001). Differences between years, however, may be due to changes in peat water content or differences in inter-annual temperature and/or precipitation. Waddington et al. (2002) found that soil respiration varied greatly at an abandoned cutover peatland in the Lac St. Jean region of Quebec. R_{SOIL} during the wet year was 24–28% of the dry year values.

Analysis of the intermediate oxidation rate by individual year (not shown) shows that the maximum oxidation occurred in 1990 and 1998. These years were 30–40% warmer than the 30 yr mean and warmer than every year since 1982 (Environment Canada, unpublished data). Summer precipitation was normal in 1990, but 15% below average in 1998. Summer (May to August) precipitation and temperature data accounted for 44% of the variation in intermediate oxidation, while precipitation alone had an r^2 of 0.26.

The birch tree intermediate oxidation rate data indicate that while the average oxidation rate for a specific year may vary, the general trend is an increase in oxidation rate towards the present (Fig. 3). It is important to consider that the presence and size of the birches may affect microsite peat oxidation. Younger birches may be more susceptible to erosion than older ones, because their root system is less developed. This would result in higher oxidation and erosion rates for young birches than for old birches. Moreover, it is possible that many of the older birches that have been strongly affected by oxidation and/or erosion are now dead and have disappeared from the record. Nevertheless, peat adjacent to the more recently invaded birch trees displays a greater oxidation rate than in peat adjacent to much older birch trees and, with the limitations considered, suggests that peat oxidation/erosion rate is now increasing.

This trend of an increasing oxidation rate with time since abandonment supports the findings of Waddington et al. (2002) and Prévost et al. (1997). However, a model created by Gilmer et al. (1998) suggests that oxidation rates decreased to zero after 10 to 15 yr post-drainage. In their model, they suggest that this occurs due to a decrease in the peat substrate quality and the supply of labile C with time. Waddington et al. (2002) did find a significant decrease in peat CO_2 production rates in laboratory incubations with time since abandonment. However, this does not necessarily mean that field R_{SOIL} will also decrease with time since abandonment. Changes in peat structure (e.g., Price and Schlotzhauer 1999) and hydrology (Price 1997) are likely larger controls on the long-term oxidation rate.

Spatial Variability in Oxidation Rate

Differences in long-term oxidation rates between and within fields are in part due to differences in local effects from wind direction and fetch, but also to microsite differences in peat quality, volumetric moisture content, and temperature (Waddington et al. 2001). Interestingly, however, there were no significant differences between deposition or long-term oxidation rates in the different plot sections (i.e., eastern, central or western). We also expected higher long-term oxidation rates in the northern (and generally drier) sections of the peat fields; however, within field peat oxidation variability was low (CV = 19.1%). The location of the field within the peatland was more important than the location within the field, yet, at least in 1999,

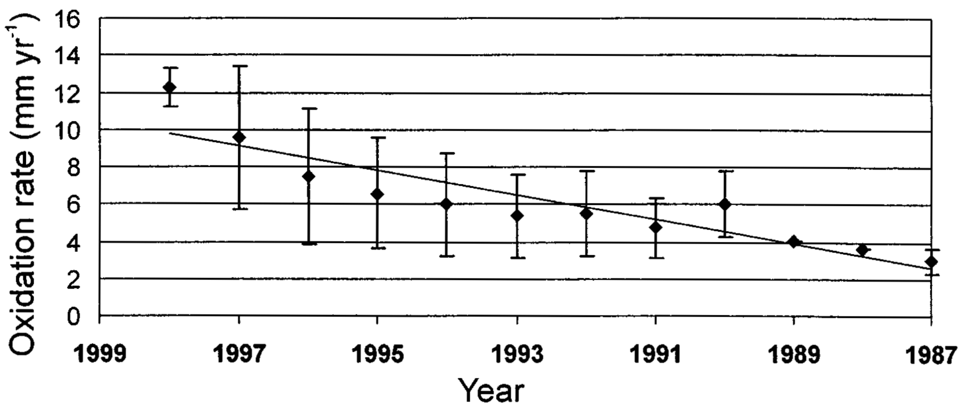

Fig. 3. Relationship between intermediate oxidation rate and age of birches. Birch age is plotted as the year of birch initiation on the peat surface.

Table 2. Soil respiration and contemporary oxidation rate for the western, central and eastern sections of the middle transect on field no. 4 and field no. 10. Values in parentheses represent on standard deviation

Field	Location	Soil respiration rate ($g\ CO_2\ m^{-2}\ d^{-1}$)	Oxidation rate ($mm\ yr^{-1}$)
4	West	6.16 (6.43)	4.76 (4.97)
4	Centre	4.13 (3.79)	3.19 (2.93)
4	East	5.09 (4.95)	3.93 (3.83)
10	West	6.69 (6.32)	4.14 (3.90)
10	Centre	6.04 (5.72)	3.74 (3.54)
10	East	8.01 (7.63)	4.95 (4.72)

wind direction and fetch did not contribute to this pattern (Campbell et al. 2002). However, the greatest deposition (Fig. 2b) still occurred in the peat field furthest downwind. Moisture content data could also be useful in explaining oxidation trends.

Restoration and Carbon Cycling Implications

Peat oxidation is an irreversible process that results in an increase in peat bulk density, a decrease in specific yield, and a decrease in hydraulic conductivity (Waddington and Price 2000). Consequently, peatland restoration should occur as quickly as possible after abandonment to minimise the effects of peat oxidation. This study indicates that peat oxidation remains constant at approximately 6.0 mm yr^{-1} with time since abandonment, which reinforces the need to begin restoration shortly after abandonment. Several studies have indicated that drained peatlands are a persistent source of atmospheric CO_2 post abandonment (eg., Nykänen et al. 1995; Silvola et al. 1996; Waddington et al. 2002). Flux magnitude results from this study are similar to this previous research. Peatland restoration can significantly reduce this CO_2 source (Waddington and Warner 2001) and can even return the peatland to a net carbon sink (Komulainen et al. 1999; Tuittila et al. 1999). The longer a peatland remains abandoned, therefore, has large long-term implications on the overall effect of peatland drainage and mining on the global carbon cycle. For example, with a mean organic content of 78% and the long-term oxidation rate of 5.8 mm yr^{-1}, we estimate that the extracted and abandoned section of the Bois-des-Bel peatland has lost ~730 t C in 19 yr.

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