Wind erosion and surface stability in abandoned milled peatlands

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Campbell, D. R., Lavoie, C. and Rochefort, L. 2002. **Wind erosion and surface stability in abandoned milled peatlands**. Can. J. Soil Sci. **82**: 85–95. Peatlands exploited for their peat by the method of milling are poorly recolonized by plants after the cessation of extraction activities, in part due to unstable peat substrates. Wind erosion has been suspected to play a role in this instability. Four studies were conducted to investigate the role of wind erosion on abandoned milled peatlands. A wind tunnel experiment was performed to evaluate the erodibility of dry, loose peat as a function of its degree of decomposition. A second wind tunnel experiment was conducted to determine how crusted peats differ in their resistance to erosion as a function of their degree of decomposition, without the input of abraders. Third, wind profiles were measured in milled, revegetated and natural peatlands in southeastern Québec to determine their aerodynamic roughness length. Finally, field measurements were made at three abandoned milled peatlands through two field seasons to characterize substrate stability and particle movement. In the wind tunnel, the erodibility of loose surface peat decreased with increasing decomposition and was predicted by their equivalent diameter to mineral particles 0.84 mm in diameter. However, once surface crusts formed, peats were all resistant to erosion. Surfaces of abandoned milled peatlands were aerodynamically smooth; therefore, exposed surface elements are subject to strong erosive forces during wind events. The greatest subsidence on abandoned milled peatlands occurred in the spring, prior to the surface movement of particles. Erosion during the summer could not be clearly detected. The instability of the peat surface remains a constraint for the restoration of abandoned milled surfaces.

Key words: Peat, cutover peatland, wind erosion, soil crusts, roughness length, soil stability

Campbell, D. R., Lavoie, C. et Rochefort, L. 2002. **Érosion éolienne et stabilité de la surface dans les anciennes tourbières commerciales**. Can. J. Soil Sci. **82**: 85–95. Les plantes recolonisent mal les tourbières dont on a récolté la tourbe une fois que les activités commerciales ont cessé, en partie à cause de l'instabilité du substrat. On soupçonne que l'érosion éolienne joue un rôle dans cette instabilité. Les auteurs ont entrepris quatre études dans l'espoir d'élucider le rôle de l'érosion éolienne dans les tourbières commerciales laissées à l'abandon. Une expérience en soufflerie a permis d'évaluer l'érodabilité de la tourbe sèche et lâche d'après son degré de décomposition. Un deuxième essai en soufflerie a contribué à déterminer de quelle façon la résistance des tourbes encroûtées à l'érosion varie avec le degré de décomposition, en l'absence d'abrasifs. Dans le cadre de la troisième étude, on a établi le profil des vents dans les tourbières exploitées, remises en végétation et naturelles du sud-est du Québec afin de préciser le paramètre de rugosité aérodynamique. Enfin, les auteurs ont pris des relevés sur le terrain dans trois tourbières commerciales abandonnées pendant deux campagnes en vue de caractériser la stabilité du substrat et les déplacements des particules. Lors des essais en soufflerie, l'érodabilité de la tourbe à surface lâche diminue à mesure qu'augmente le degré de décomposition et les particules se déplacent comme des particules minérales de 0,84 mm de diamètre. Une fois qu'une croûte s'est formée à la surface cependant, toutes les tourbes résistent à l'érosion. Les anciennes tourbières commerciales ont une surface aérodynamique lisse, si bien que les éléments exposés, en surface, subissent une force d'érosion importante quand il vente. La plus grande subsidence des tourbières abandonnées a été notée au printemps, avant que les particules à la surface ne commencent à se déplacer. Les auteurs n'ont pas vraiment décelé d'érosion en été. L'instabilité de la tourbe en surface continue de poser un problème pour la restauration des anciennes tourbières commerciales.

Mots clés: Tourbe, tourbière exploitée, érosion éolienne, encroûtement du sol, paramètre de rugosité, stabilité du sol

Peatlands in Canada and northern Europe have been drained and cleared over extensive areas for agricultural production or peat extraction (Lappalainen 1996). After drainage has ceased, subsidence of these peatlands continues (e.g. Mirza and Irwin 1964; Millette 1976; Irwin 1977; Schothorst 1977; Parent et al. 1982; McLay et al. 1992; Price and Schlotzhauer 1999; McNeil et al. 2000). This long-term subsidence is usually attributed to shrinkage, compression and biochemical oxidation of the peat (Schothorst 1977). However, wind erosion can also be an important cause of subsidence, at least in agricultural settings when the soil is dry and broken by farm machinery (Irwin 1977; Lucas 1982; Parent et al. 1982). In comparison with mineral soils, wind erosion of organic soils has received scant attention. It has only recently been considered in milled peatlands (McNeil et al. 2000).

Peat is usually extracted from peatlands using the modern method of milling (Crum 1988, pp. 182–188; Frilander et al. 1996). A peatland is first drained by ditching at 20–40 m intervals and the surface vegetation is removed. The soil surface is repeatedly harrowed to a depth of 5 to 10 cm to break up and dry the peat. In North America, the milled peat is then collected using vacuum collectors. In this manner, 5 to 10 cm of peat may be removed per year over several decades. In Canada, once milled peatlands are abandoned, fibric to sapric, sphagnum or sedge peat deposits remain (usually <1 m deep), often with a surface layer of harrowed peat. Milled surfaces are large (up to 5 km^2), flat and bare of vegetation. Their subsequent recolonization by plants is very slow (Salonen 1987; Desrochers et al. 1998). Although several barriers have been invoked to explain this problem, the instability of the abandoned substrate appears to be a critical factor (Rochefort 2000). Wind erosion has been suspected to cause, in part, this surface instability. First, the lack of vegetation, long fetches and relatively smooth surfaces should allow strong erosive forces near the surface during high winds. Peat is also very light when dry (Puustjarvi and Robertson 1975), and crusted organic soils are fragile as compared to mineral soils (Zobeck 1991a). Furthermore, we have observed particle movement over abandoned milled surfaces when conditions were especially dry. Finally, thicker deposits of loose peat have been found near forest edges downwind of a milled bog, possibly due to deposition of wind-eroded peat (McNeil et al. 2000).

Wind erosion involves the interplay between the atmosphere and the ground surface. Wind decreases in velocity near the surface due to frictional drag of the air over the surface elements (Oke 1987, p. 54). This produces a shearing stress, the strength of which depends on wind velocity, air density and surface roughness. Each rigid and homogeneous surface has a characteristic roughness length (z_0), determined from the wind profile. Smooth surfaces have small roughness lengths and consequently steep velocity gradients above the surface during wind events. An exposed particle on such a surface is subjected to the combined atmospheric forces of drag in the direction of the wind, rotation about the particle's axis and lift upwards (Greeley and Iversen 1985, p. 71). Particle movement begins when these forces exceed particle weight and cohesive forces bonding it to other particles. Particles move by suspension, saltation (lift-off and return to the surface) or surface creep. Those in saltation collide with others on the surface and accelerate erosion downwind (Chepil and Milne 1941). However, after rainfall, soil particles bind together forming thin surface crusts once dry, which are much more resistant to wind erosion (Zobeck 1991b).

The general objective of this study was to evaluate the role of wind erosion in the surface instability of abandoned milled peatlands. Four studies were conducted. First, a wind tunnel study was conducted to evaluate how the erodibility of loose, dry peat varies as a function of the degree of decomposition of the peat. The degree of decomposition is the primary parameter determining the physical properties of peat, including particle size and density (Puustjarvi and Robertson 1975). A second wind tunnel study was conducted to determine how dry, crusted peats resist wind erosion as a function of their degree of decomposition. Third, the characteristic roughness length (z_0) was measured in milled peatlands, as well as in revegetated and natural peatlands, to evaluate the potential for strong erosive forces. Finally, the surface stability and particle movement was measured in abandoned milled peatlands over two summers in order to quantify the role of wind erosion in their subsidence.

METHODS

Wind Tunnel Experiments

Samples of milled surface peat were collected during July 1999 from actively milled peatlands in the Rivière-du-Loup bog in eastern Québec (47°48′N, 69°31′W). Their degree of decomposition was determined on the von Post scale from peat just below the milled layer. In the von Post test, the decomposition of peat is evaluated along a nine-point scale by squeezing peat in the hand and determining water colour, quantity of extruded material, fibre content and distinctiveness of plant fragments (Parent and Caron 1993). Three replicate samples of milled peat of von Post 3, 4, 5 and 6 were collected for a total of 12 samples. A poorly decomposed peat of von Post 3 is light brown in colour with many long fibres, while a more decomposed peat of von Post 6 is almost black and has low fibre content (Puustjarvi and Robertson 1975). Milled peat was collected with a garden rake and placed in large plastic bags for transport to the wind tunnel facility. Replicate samples were collected in different milled peatlands where possible, and if not, at least 50 m apart on different peat fields.

Gravimetric water content and fresh and dry bulk density were measured for 170-cm^3 samples of milled peat by weighing them fresh and after being dried at 105°C for 24 h (Parent and Caron 1993). A particle size distribution of each peat sample was determined using a wet sieving method, which allowed for the gentle separation of peats into their smallest component particles. Peat samples were rewetted with the help of a detergent, stirred for over 2 h, then sifted under water using a series of flat sieves with openings of 6.35, 4.00, 2.36, 1.68, 0.84, 0.36 and 0.15 mm. The size distribution of aggregates was also determined for each sample using a dry sieving technique. Samples were gently sifted dry using a series of flat sieves with openings of 9.50, 6.35, 4.75, 4.00, 2.80, 2.36, 1.68, 0.84, 0.36 and 0.15 mm. For both sieving techniques, fractions were dried at 105°C for 24 h, and expressed as percentages of the pre-sieved dry total.

Wind tunnel tests were conducted at the Trent Wind Tunnel in Peterborough, Ontario. The facility consists of an open loop, suction-type wind tunnel with a 13 × 0.71 × 0.76-m working section designed for simulation of boundary layer flow (for specifications see: http://www.trentu.ca/geography/windsimExpl.html). The exit of the wind tunnel was fitted with a stainless steel mesh with 0.129-mm openings to capture all larger particles in a settling chamber. For each experiment, trays were first prepared in the following manner. Peat samples were dried for 3 d in a glasshouse. Each peat sample was then placed in a tray 200 × 35 × 2.7 cm in size, and the surface was smoothed. For the loose peat experiment, peat-filled trays were left to air dry for 36 h prior to testing. For the crusted peat experiment, peat-filled trays were sprayed with 2 L water in a fine mist (2.8 mm precipitation), and left to air dry for 36 h. This treatment produced a thin (2–3 mm) dry crust at the peat surface.

Both the loose peat and the crusted peat experiments followed a random complete block design with four peat types and three blocks. To test each sample, a peat-filled tray was placed in the wind tunnel so that the sample surface was level with the floor of the wind tunnel. Each run at a particular wind velocity lasted 180 s. The sample was subjected to an initial run at a freestream velocity of 2.8 m s^{-1}, as measured at 40 cm height. Freestream velocity was increased by ~2 m s^{-1} in subsequent runs to maxima of 10.4 ± 0.7 m s^{-1} and 12.4 ± 0.1 m s^{-1} (mean ± SD) in the loose and crusted peat experiments, respectively. Lower maximum wind speeds were attained during the loose peat experiment due to the clogging of the exit filter by eroded peat. After each run, eroded peat was carefully collected from the settling chamber, and its weight was determined after drying at 105°C for 24 hours. Following the final run of each experimental tray, a 155 cm^3 subsample was collected to determine gravimetric moisture content and fresh and dry bulk density, as above. Measurements of eroded peat were converted to a volume basis using the dry bulk density in order to compare the volume of eroded peat between the different peat types.

Following the loose peat experiment, aggregate size distributions were determined for peat eroded at the maximum set velocity (10.4 ± 0.7 m s^{-1}; mean ± SD), using the same dry sieving method used above. This attained velocity is close to that of 11.2 m s^{-1} used by Chepil (1950) to determine the erodibility limit of 0.84 mm in diameter for particles of mineral soil. The equivalent diameter to mineral soil particles of 0.84 mm size was calculated for each peat sample following Chepil and Woodruff (1963) by multiplying the actual diameter of a peat aggregate by the ratio of the bulk density of the peat to that of quartz sand (2.65 g cm^{-3}). Fresh bulk density of each peat sample was used to approximate apparent aggregate density (Chepil and Woodruff 1963, p. 237).

Data for the wind tunnel experiment were analysed using the GLM procedure of SAS statistical software (SAS Institute, Inc. 1996–1999). Fresh and dry bulk density, and water content of field and experimental peats were analysed together as a function of their degree of decomposition on the von Post scale using analyses of variance (ANOVA) with a priori polynomial contrasts. Roughness lengths were analysed versus their degree of decomposition using separate ANOVA with a priori polynomial contrasts and repeated measures ANOVA. For both experiments, volumes of eroded peat per wind tunnel run were log-transformed ($\log_{10} x + 0.1$), then analysed versus their degree of decomposition using repeated measures ANOVA. All tests were considered significant at $P < 0.05$.

Field Studies

Study Area

Field measurements were made at four sites near Rivière-du-Loup in eastern Québec. The Saint-Modeste (SM) site (47°52′N, 69°27′W) was a 23-ha milled peatland abandoned since 1987, adjacent to a 36-ha actively-milled peatland (Fig. 1). A fringe of forest 5 to 15 m high surrounded the milled peat surface. The site was flat with widely spaced

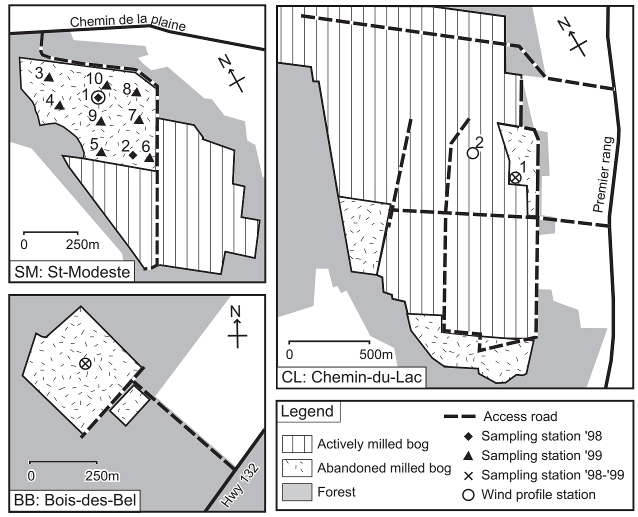

Fig. 1. Study sites near Rivière-du-Loup, Québec, showing stability and wind profile measurement stations.

ditches and almost bare of vegetation (<1% cover). The surface peat in the abandoned section consisted of fibric sphagnum peat (von Post 3 to 4), and peat thickness exceeded 1.2 m. A wind profile was measured at one station in 1998. Stability was measured at two stations in 1998 and at eight stations in 1999 to obtain a better idea of stability across the abandoned milled surface. Maximum fetch was 0.7 to 1.2 km from the south.

The Bois-des-Bel (BB) site (47°48′N, 69°31′W) was an 11-ha milled peatland abandoned since 1980 (Fig. 1), and surrounded by forested peatland with ~10 m tall trees. The milled surface was flat with a considerable amount of woody debris. Fibric sphagnum peat (von Post 3 to 4) was present at the surface, and peat thickness was over 1 to 3.5 m. Vegetation was sparse (<1 to 3%) and dominated by birch (1 to 3 m tall), ericaceous shrubs and cottongrass (*Eriophorum vaginatum*) tussocks. Maximum fetch was 0.25 km from the south.

The Chemin-du-Lac (CL) site (47°45′N, 69°31′W) was a small abandoned milled surface located along the periphery of a large actively-milled peatland (>3 km^2; Fig. 1). The surface peat varied from fibric to hemic sphagnum and sedge peat (von Post 4 to 6), and peat thickness was as little as 0.2 m over clay. Surface stability was measured in 1998 and 1999 on abandoned sedge peat 15 m from the edge of actively milled peatland. This station was protected from the wind to the east by herbs 20 m away (<1 m tall), but had fetches of over 2.5 km from the north and 0.25 to 0.5 km from the south and west before reaching elevated access roads (1–3 m tall). Wind profiles were measured over the abandoned surface (CL1) and in a large flat section of the actively milled peatland (CL2).

Wind profiles were also measured at two stations at the Président Ouest (PO) site (47°48′N, 69°31′W). The first station was in a 19-ha section of abandoned milled peatland, well-recolonized (90% cover) with *Eriophorum angustifolium*, *E. vaginatum* and *Carex canescens*. The last two species

Table 1. Wind profile parameters measured in actively milled, abandoned and natural peatlands near Rivière-du-Loup, Québec. The R^2 values indicate the fit between the mean measured and calculated wind speed profile

Station	Surface characteristics	Plant cover (%)	Fetch (m)	Measurement duration (min)	Zero plane displacement (d) (mm)	Roughness length (z_0) (mm)	Friction velocity (u_*) (m s^{-1})	R^2
CL1	Abandoned, but 15 m from milled zone	<1	250	43	–3	3.6	0.40	0.98
CL2	Actively milled	0	300	45	4	5.2	0.45	0.99
SM1	Abandoned with little woody debris	0	250	71	4	2.1	0.32	0.98
BB	Abandoned with much woody debris and scattered birches, cottingrass and ericaceous shrubs	<1–3	180	74	–3	18.8	0.38	0.99
PO1	Abandoned with rhizomatous and tussocky cottongrass and sedges	90	370	53	14	41.3	0.60	0.99
PO2	Natural bog with *Sphagnum* hummocks, low ericaceous shrubs	100	330	39	14	40.9	0.65	0.99

are tussock-formers, producing scattered dense obstacles around 15 cm tall. The second station was located nearby in a 21-ha open natural bog remnant with 10–15 cm tall hummock-hollow topography and 100% cover by *Sphagnum* mosses and ericaceous shrubs.

Temperature and precipitation data are available up until 1998 for the Saint-Arsène meteorological station (47°57′N, 69°23′W; 1961–1990 normals: Atmospheric Environment Service (AES) 1993; detailed data: Environment Canada, unpublished) and for 1999 from the Bois-des-Bel study site (M. Waddington, McMaster University, unpublished data). Highest monthly mean temperatures were attained in July 1998 (17.6°C), and June 1999 (17.4°C). In both years, August was the driest summer month (57.7 and 32.7 mm in 1998 and 1999, respectively). Normals of wind data (1951–1980) are available for the Rivière-du-Loup airport (47°48′N 69°33′W; AES 1982). Prevailing wind direction in May is from the north and in June to September from south to southwest. Mean wind speeds at 10.1 m height from May to September are 12 to 13.5 km h^{-1} (3.3 to 3.8 m s^{-1}), and maximum sustained hourly speeds are 45 to 58 km h^{-1} (12.5 to 16.1 m s^{-1}).

Wind Profiles

Wind profiles were measured in September 1998 on cloudy days with temperatures of 11 to 17°C and mean wind speeds of 3.5 to 6.8 m s^{-1} at 2.23 m height. As a result of the windy, cloudy conditions, profiles were considered to have been measured under neutral atmospheric conditions (Oke 1987, pp. 51–55). Wind speeds were measured using five Gill three-cup anemometers installed on a mast at log heights of 0.449, 0.670, 1.000, 1.492 and 2.226 m above the surface. These were connected to a datalogger (model 23X, Campbell Scientific Inc.), and simultaneous wind velocity measurements were taken at 15-s intervals for 39 to 74 min, depending on the site (Table 1). Mean wind speeds were calculated over the entire measurement period. Wind profile parameters were then calculated from the logarithmic equation (Oke 1987, p. 116):

$$u_z = (u_*/k)\ln[(z - d)/z_0] \quad (1)$$

where u_z = mean wind velocity at a given height z; u_* = friction velocity; k = Von Karman's constant (0.40); d = zero plane displacement height; and z_0 = roughness length. Parameters u_*, d and z_0 were chosen using a least squares fit technique (Stearns 1970). Values of these parameters were substituted into Eq. 1 and those that produced the highest R^2 between calculated and measured mean wind speeds were chosen as the best solution.

Surface Stability

Stations were sampled in 1998 at approximately 1-mo intervals from 16 June to 3 October, and in 1999 at approximately 2-wk intervals from 14 May to 29 September. Five measurements were taken at each station and sampling date: 1) gravimetric water content of surface peat, 2) dry bulk density, 3) change in surface elevation and microtopography, 4) amount of saltating particles, and 5) amount of wind blown dust. Gravimetric water content and dry bulk density were measured twice at each station by taking two 170-cm^3 samples of surface peat to a depth of 4.3 cm. Changes in surface elevation and microtopography were determined after all ground frost had melted using a horizontal wire installed parallel to the peat surface. The horizontal wire consisted of a 30-cm section of stiff wire elevated ~10 cm above the peat surface. The wire was attached to supports on both ends that rested on the peat surface. The base of each support consisted of a rectangular frame of stiff wire covered with cloth to prevent undercutting erosion, and was firmly anchored to the surface with 10-cm-long pins. Bases of each support remained flush with the initial, cloth-covered surface throughout the field season. Height to a 3-mm diameter point on the surface was measured to 1 mm precision at ten 3-cm distant points along the wire. At each measurement station in 1998, four horizontal wires were installed 6 m apart across the width of a peat field. In 1999, only two horizontal wires were installed per station and located 20–30 m apart.

Deposition of particles transported by saltation was measured between sampling periods using pitfall traps. They consisted of 1-L plastic containers sunk into the peat surface with 1 cm protruding above the surface to prevent the capture of peat during rain events. The mouth of these containers was 10 cm in diameter and a baffle was placed inside the trap to prevent the escape of deposited peat. In 1998, four pitfall traps were placed 6 m apart at each station, while in 1999 only two pitfall traps were installed 20 to 30 m apart at each station.

Wind-blown dust was captured between sampling dates using Fryrear traps (Fryrear 1986), modified with rain hoods (Shao et al. 1993). Air and particles enter these traps through a 10-cm^2 opening directed windward by a weather-vane. The air exits via a 60-µm screen, capturing larger dust particles. Their efficiency compares favourably to other dust trapping devices (Shao et al. 1993). In 1998, three traps were placed at each station on a mast with the base of their openings at heights of 0.15, 0.37 and 1 m in order to determine the optimal trap height. This height was found to be 0.15 m, and in 1999 only one Fryrear trap was installed per station at this height.

RESULTS

Wind Tunnel Experiments

Peat Characteristics

Fresh and dry bulk densities increased linearly with increasing degree of decomposition (Fig. 2a and 2b). Bulk densities of field peat were, however, always lower than those of peat in experimental trays. Water content of the peat decreased linearly with increasing degree of decomposition (Fig. 2c). Tray peats were not significantly different from each other, but were significantly drier than field peats. Particle size distributions of peat samples as determined by wet sieving varied with the degree of decomposition (Fig. 3). More decomposed peats had a higher proportion of finer particles, especially those less than 0.15 mm in size. One sample of von Post 6 was composed of strong aggregates that could not easily be broken down to the finest particles, and as such, the particle size distribution of this peat appears coarser. Only slight differences were observed in size distributions of aggregates between peats of increasing degree of decomposition (Fig. 3).

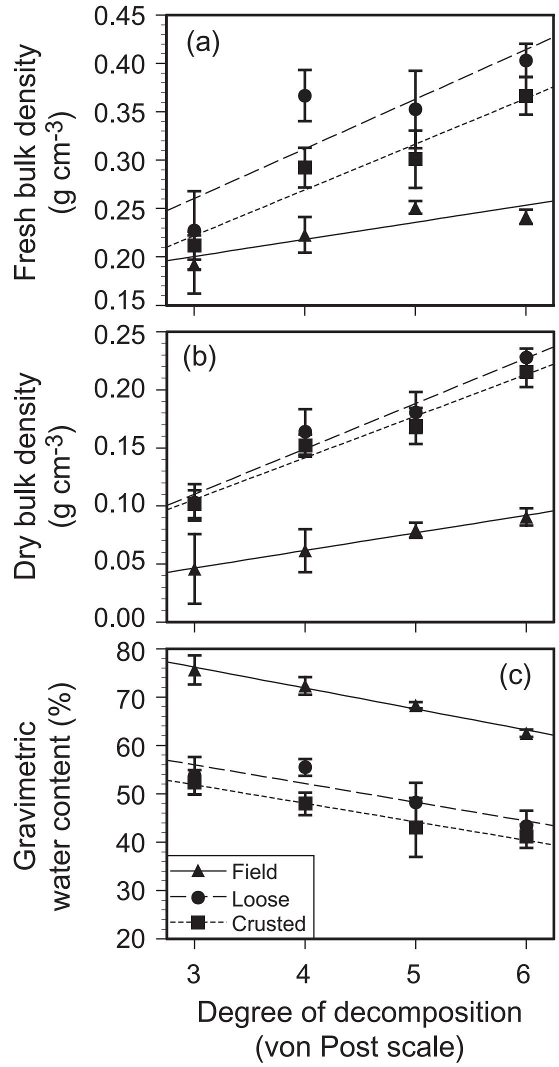

Fig. 2. Mean values of (a) fresh bulk density, (b) dry bulk density and (c) gravimetric water content of peats of increasing degree of decomposition as measured on the von Post scale for samples of milled field peat (triangles), loose peat in experimental trays (circles) and crusted peat in experimental trays (squares). Overall standard errors are shown.

Loose Peat Experiment

During initial runs at the lowest wind speed (2.8 m s^{-1}), roughness length (z_0) of the trays decreased linearly with increasing degree of decomposition of the peats. However, in all following runs (>4.6 m s^{-1}), there was no difference in roughness between peats. Roughness lengths in all trays decreased with increasing wind speed, likely due to deflation of the peat surface by erosion. Peat in this experiment easily eroded from the trays (Fig. 4). Eroded volume increased with increasing wind speed, but the overall erosion patterns as determined by repeated measures analyses were not significantly different between peats of increasing degrees of decomposition. Neither are differences apparent between peat types in the threshold velocities of initial particle movement (Fig. 4). However, size distributions of aggregates eroded at the highest wind velocity differed from aggregates of milled peat in experimental trays (Fig. 3). A size limit of erosion is apparent for each peat type, above which little peat was eroded. The 99% percentile size limit decreases with increasing decomposition on the von Post scale (Fig. 5). Loose particles of poorly decomposed peats are lighter, consequently larger particles are eroded as compared to more decomposed peats. These actual size limits closely follow the limits of erodibility of the peats predicted by their equivalent diameter to particles of mineral soil 0.84 mm in size, as calculated from their bulk densities relative to mineral soil (Fig. 5).

Crusted Peat Experiment

At all wind speeds, roughness length (z_0) of the trays decreased linearly with increasing degree of decomposition

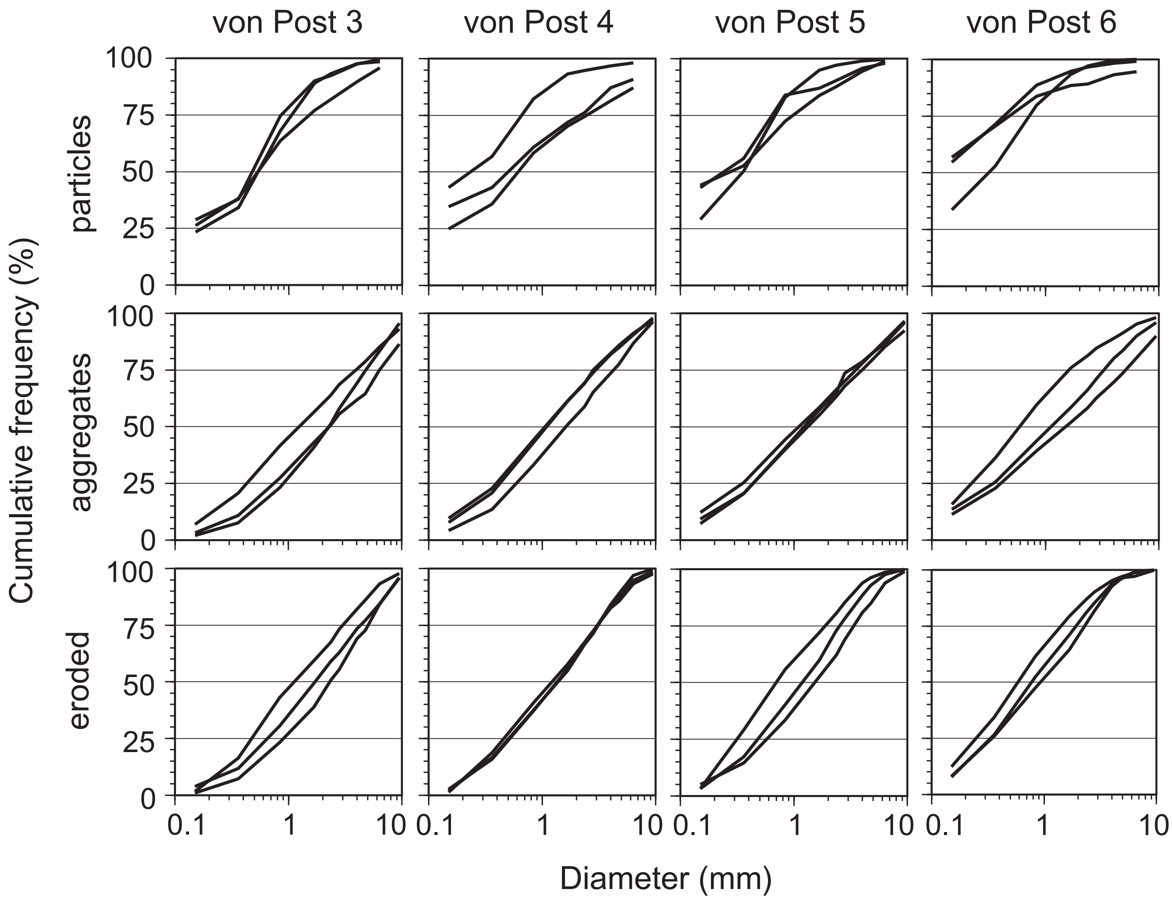

Fig. 3. Cumulative size distributions of particles of milled peat (top row), aggregates of milled peat (middle row) and aggregates of peat eroded during the loose peat wind tunnel experiment at an attained velocity of 10.4 ± 0.7 m s^{-1} (mean ± SD; bottom row), for peats of increasing degree of decomposition on the von Post scale.

of the peats. The roughness length also decreased with increasing wind speed, even though little or no deflation was observed, possibly due to elastic compression of the peat at high wind speeds. Throughout this experiment, the crusted peat surfaces were very resistant, with very little erosion of peat, even at attained freestream velocities over 12 m s^{-1} (Fig. 4). Eroded peat volumes were 50- to 100-fold less than in the loose peat experiment. Peat eroded mostly from the leading edge of the trays as plaques, due to edge effects of the trays. The overall erosion pattern as determined by repeated measures analyses was not significantly different between peat types. Neither were there differences in threshold velocities of initial particle movement nor in volumes eroded at the highest wind velocity tested. Particle size distributions of eroded aggregates could not be determined due to insufficient volumes of eroded peat.

Field Wind Profiles

Wind profiles measured in milled peatlands closely matched the expected linear relationship between wind speed and the natural logarithm of height (R^2 > 0.97; Table 1). Actively milled surfaces had similar roughness lengths (z_0) as unvegetated, abandoned milled peatlands with little woody debris. Roughness length was much higher over rougher surfaces, as seen at Bois-des-Bel, which had considerable woody debris. At the revegetated milled peatland and natural peatland at Président Ouest, the profile was displaced upwards by 14 cm as a result of the vegetation cover. The roughness length of the revegetated milled peatland was remarkably similar to that of natural peatlands, even though there was considerable difference in the vegetation (rhizomatous and tussocky cottongrasses and sedges versus *Sphagnum* hummocks with low ericaceous shrubs).

Stability of Milled Surfaces

The 1999 data for Saint-Modeste illustrate the general patterns observed of surface stability. In mid-May, the surface was initially smooth to, more commonly, bumpy in appearance (Fig. 6). This roughness is also reflected in the initial within-wire standard deviation (Fig. 7). The seasonal progression of the surface can be divided into a “spring” phase from May to mid-June and a “summer” phase from mid-June to the end of September (Fig. 7). During the spring phase, the mean elevation of the peat surface dropped by 4.2 mm. However, moisture remained unchanged at around 80%, and almost no material was caught in pitfall or Fryrear traps. During the summer phase, there was a smaller drop in the peat surface of 2.7 mm. The surface became smoother as

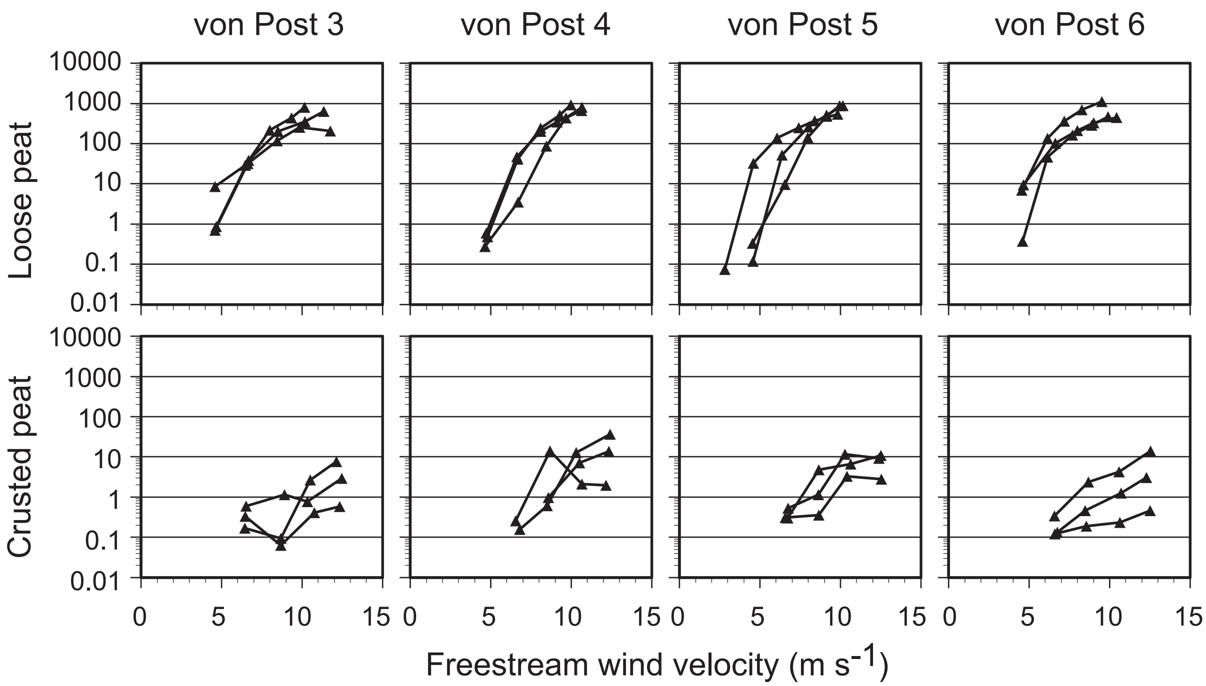

Fig. 4. Loss of volume sequences as a function of freestream velocity in the wind tunnel for loose peats (top row) and crusted peats (bottom row) of increasing degree of decomposition on the von Post scale.

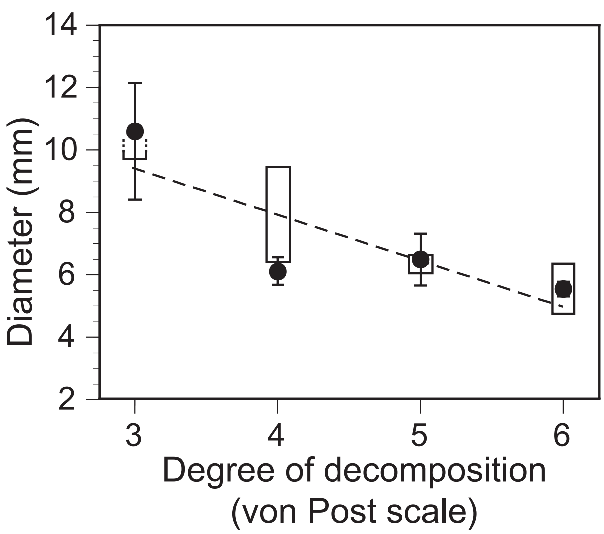

Fig. 5. Largest predicted (circles) and actual (rectangles) aggregate sizes of peat eroded in the loose peat experiment as a function of their degree of decomposition on the von Post scale. Predicted largest aggregates were determined by calculating the equivalent diameter for each peat corresponding to mineral soil particles of 0.84 mm in diameter (mean ± SE). Fresh bulk density values from the loose peat experiment were used in the calculations. Actual largest peat aggregates were determined from the 99% percentile of aggregate size distributions for peats eroded in the wind tunnel at 10.4 ± 0.7 m s^{-1} (mean ± SD, n = 12; Fig. 3). The rectangles show the range of largest particle sizes for the three replicates. For peats of von Post 3, only one of the three samples reached this 99% limit at 9.5 mm.

the season progressed (Fig. 6), which is also reflected by the reduction of the within-wire standard deviation (Fig. 7). The surface dried, reaching a mean water content of 68% by early September. Dry bulk density of surface peat remained unchanged throughout both phases (0.14 ± 0.01 g cm^{-3}, mean ± SD). Dust and larger particles were captured at most stations during this period. Most dust was collected in Fryrear traps adjacent to the actively milled sites (stations SM5 and SM6), but larger particles were mostly collected in pitfall traps furthest from the milled area (station SM3). Overall, the weekly rate of subsidence in 1999 during the “spring” phase was over sixfold greater than during the “summer” phase (Table 2). In 1998 and 1999, rates of subsidence in the summer were similar although more variable due to deposition at some sites. In 1998, less peat was captured in the Fryrear and pitfall traps than at most stations in 1999. The moisture content of the surface peat in 1998 reached a minimum of 65 ± 12 % (mean ± SD), similar to that in 1999.

At Bois-des-Bel, the general patterns were similar to Saint-Modeste in 1999, with definite spring and summer phases of surface subsidence (not shown), but rates of subsidence were approximately double than at Saint-Modeste for both years (Table 2). Rates of subsidence during the summer were similar in 1998. For both years, however, little peat was caught as dust or larger particles (0.25 g cumulative total in Fryrear trap, 2 g biweekly maximum in pitfall traps in 1999). The moisture content of the surface peat reached a minimum of 50 ± 9% and 60 ± 11% (mean ± SD) in 1998 and 1999, respectively. Dry bulk density remained unchanged (0.15 ± 0.00 g cm^{-3}, mean ± SD).

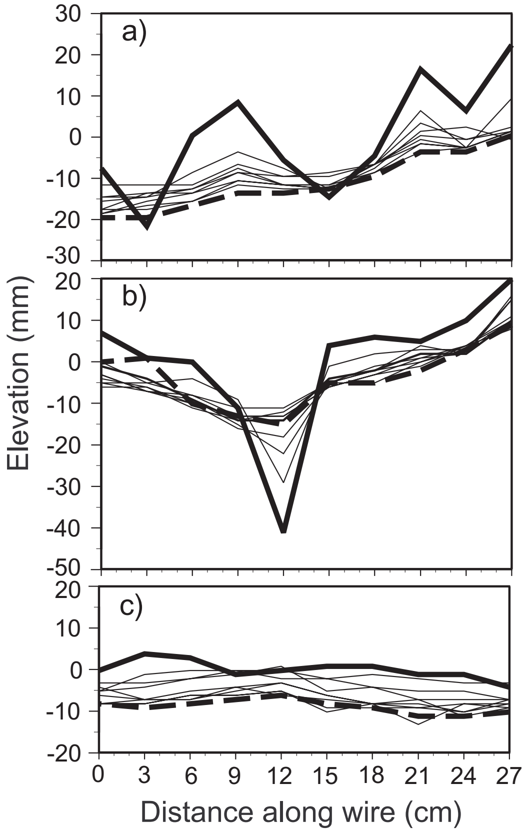

Fig. 6. Three microtopographic profiles of milled peat surfaces found at the Saint-Modeste site, Québec, in 1999 showing a range of typical surface changes: (a) subsidence and smoothing of bumpy microtopography; (b) subsidence and filling of cracks; (c) subsidence of a flat surface. The thick solid line is the initial surface profile in mid-May (Julian day 134), and the thick dashed line is the surface profile in late September (Julian day 272). Thin solid lines are profiles at intermediate dates.

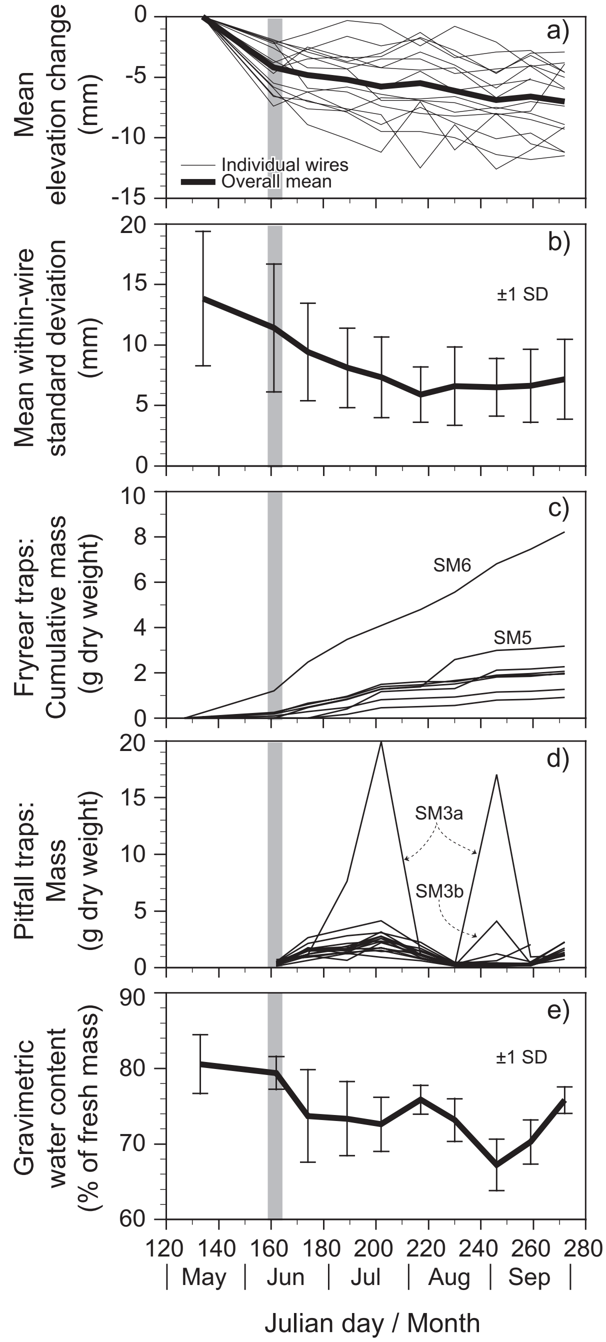

Fig. 7. Summary of surface stability data for the Saint-Modeste site, Québec, in 1999. Shown are (a) the mean elevation changes of the surface as measured from individual horizontal wires (n = 16) and the overall mean elevation change; (b) the overall within-wire standard deviation of surface elevation (n = 16; mean ± SD); (c) the cumulative dry mass of dust collected in Fryrear traps at sampling stations (n = 8); (d) the dry mass of peat collected in pitfall traps (n = 16); and (e) the gravimetric water content of the surface peat (n = 16; mean ± SD). The broad grey line indicates the transition between the spring phase when no peat movement is observed and the summer phase when peat movement begins.

At Chemin-du-Lac, the patterns of stability were different than at other sites. In 1999, there was no difference in the rate of subsidence between spring and summer (Table 2), but subsidence was fourfold higher than in 1998. For both years, there was a great deal of peat trapped as dust or as larger particles. In 1998 and 1999, respectively, there were totals of 16 g and 11 g caught in the Fryrear traps, and maxima of 125 g (monthly, 1998) versus 16 g (biweekly, 1999) caught in pitfall traps. In both years, ditches were partly filled with peat after mid-summer windstorms. This site was also the driest with water content of surface peat dropping to 40 and 55% in 1998 and 1999, respectively. Dry bulk density remained unchanged throughout the season (0.22 ± 0.00 g cm^{-3}, mean ± SD).

DISCUSSION

Erodibility of Milled Peats

The wind tunnel experiments show that loose and dry milled peat is easily eroded by wind. However, differences in threshold velocity of initial particle movement were not found between peats of increasing degree of decomposition. Differences may exist, but more samples and smaller incre-

Table 2. Changes and rates of change of surface elevations of milled peatlands near Rivière-du-Loup, Québec, during the 1998 and 1999 field seasons (mean ± SD), as measured using several horizontal wires placed parallel to the surface. Measurements are made with respect to the initial surface. For 1999, overall values are shown as well as values for the spring period (Julian day 134 to 161, i.e., 14 May to 10 June) versus the summer period (Julian day 161 to 272, i.e., 10 June to 29 September)

		Saint-Modeste			Bois-des-Bel			Chemin-du-lac		
Year	Julian date	*n*	Change (mm)	Rate (mm wk^{-1})	*n*	Change (mm)	Rate (mm wk^{-1})	*n*	Change (mm)	Rate (mm wk^{-1})
1998	167–283	8	–3.1 ± 10.8	–0.18 ± 0.65	4	–6.5 ± 2.5	–0.39 ± 0.15	4	–2.0 ± 1.2	–0.12 ± 0.07
1999	134–161	16	–4.2 ± 1.9	–1.09 ± 0.50	2	–7.1 ± 0.4	–1.83 ± 0.09	2	–2.0 ± 1.9	–0.51 ± 0.49
1999	161–272	16	–2.7 ± 3.0	–0.17 ± 0.19	2	–5.0 ± 2.5	–0.31 ± 0.16	2	–7.5 ± 1.1	–0.47 ± 0.07
1999	134–272	16	–6.9 ± 2.9	–0.35 ± 0.15	2	–12.0 ± 2.1	–0.61 ± 0.11	2	–9.5 ± 3.0	–0.48 ± 0.15

mental increases in wind velocity would be required to detect them. Differences between peats did become evident at high wind speed. The concept of a 0.84 mm equivalent diameter limit for erodible particles (Chepil 1950; Woodruff and Siddoway 1965) appears to apply well to light aggregates such as peats, even though they are six- to tenfold lighter than mineral soils. Their erodibility at high wind speeds decreases with increasing degree of decomposition, as a result of the increasing particle density. The erodibility of loose peats at high wind speed can be evaluated simply by measuring their fresh density. However, problems may exist in scaling-up this conclusion to the field situation. Roughness lengths over the peat surfaces in the wind tunnel were two to three orders of magnitude lower than those observed in the field, and wind velocities were very high. Consequently, smaller peat particles may erode in the field situation.

Once even a thin crust is formed after being rewetted and dried, all peats became very resistant to erosion by wind in the wind tunnel. Because crust strength increases with rainfall intensity (Farres 1978), crusted peats in the field should be even more resistant to wind erosion because they periodically receive more intense rainfall than that applied in the wind tunnel experiment. It is expected that fibric peats would be more resistant to erosion by abrasion due to their higher fibre content.

Roughness of Milled Surfaces

In term of roughness lengths (z_0), milled peatlands with little woody debris more closely resemble agricultural fields tilled by disks (z_0 = 1.6 to 2.7 mm; Saleh et al. 1997) or fallow ground (z_0 = 1–4 mm; Wieringa 1993) than natural bogs with their hummock-hollow topography. Steep wind velocity gradients consequently occur near the surface of milled peatlands during wind events, producing strong erosive forces. Climate normals for wind (AES 1982) show that strong wind events do periodically occur during the summer. Particles on the surface would be subject to strong drag and lift during windstorms, favouring their movement.

Woody debris increases the roughness length substantially and should provide protection against wind erosion. However, once milled peatlands are revegetated with rhizomatous and tussocky cottongrasses and sedges, their roughness length essentially returns to values that characterize natural bogs, at least at high wind speeds. In sufficient density and aerial extent, rhizomatous and tussock-forming species therefore act to restore wind velocity gradients and consequent momentum and energy transfer over milled surfaces. This may explain in part their efficiency as companion plants for the restoration of bog plant communities (Grosvernier et al. 1995).

Role of Wind Erosion in Subsidence

Surfaces of milled peatlands near Rivière-du-Loup subsided during spring and summer 1998 and 1999, but this phenomenon could not be clearly linked to wind erosion. The subsidence during the spring phase in 1999 at Saint-Modeste and Bois-des-Bel occurred prior to any movement of particles on the surface and was greater than during the summer. This subsidence may have been even greater, because measurements only began in late spring. The peat surface did not dry substantially during this spring period, indicating that shrinkage of the peat upon drying did not play a major role in the subsidence process, as is sometimes observed (Schothorst 1977). The initial bumpy appearance of the peat surface appears to have been caused by needle ice that is commonly observed in milled peatlands during the spring and fall (E. Groeneveld, Université Laval, pers. comm.). Organic soils are especially prone to disturbance by needle ice formation (Brink et al. 1967). It is possible that the spring subsidence is related to the consolidation of surface peat after the melting of needle ice, although further study is required to test this hypothesis.

During the summer phase, when the surface dried, there was no strong evidence of wind erosion of abandoned surfaces. No sudden changes in surface elevation were observed as would be expected if erosion occurred during strong wind events. Wind speed was not monitored during field seasons, but windstorms did occur. At Bois-des-Bel, the summer subsidence (6.5 mm in 1998; 5.0 mm in 1999) was similar to the mean subsidence rates measured at that site in 1999 using different techniques (5.8 to 6.8 mm yr^{-1}; McNeil et al. 2000). Carbon oxidation was used apparently sufficient to explain subsidence observed at Bois-des-Bel. This may also be the case for Saint-Modeste. However, the observed accumulation of loose peat at the downwind edge of the Bois-des-Bel peatland (up to 3.8 mm), suggests that displacement of surface peat by wind has taken place, at least over the long term. The Chemin-du-Lac site was the driest and had by far the most captured peat particles, yet there is no clear pattern of subsidence by wind erosion. Inputs of particles from adjacent actively milled fields were certainly plentiful at this site, and deposition of particles may have compensated for any wind erosion that might have occurred.

Several factors may have helped to stabilize the surface during both summers. Surface crusts most likely played a key role, because they dramatically reduce the erodibility of dry peat, as observed in the wind tunnel experiment. Surface moisture was also likely important. Peat is very absorbent (Puustjarvi and Robertson 1975); therefore, regular precipitation would increase peat density and reduce its erodibility. Furthermore, moist soils have stronger cohesion than dry soils as a result of adsorbed water films (Chepil 1956). Periods of greatest particle movement did occur when surface peat was driest. It is therefore possible that wind erosion only becomes important in abandoned milled peatlands during drought years.

CONCLUSIONS

This study demonstrates that peat is highly erodible when loose and dry. The erodibility of different peats can be evaluated by determining their fresh density and proportion of aggregates less than 0.84 mm in equivalent diameter. Abandoned milled surfaces are also aerodynamically smooth with consequent steep velocity gradients above the surface during wind events. However despite these favourable conditions, wind erosion during the summer was not an important cause of subsidence in milled peatlands. This was probably due, in part, to the crusting of the surface that makes them very resistant to wind erosion. It is possible that wind erosion takes on a more important role during drought years. Nevertheless, surfaces of abandoned milled peatland still appear to be unstable, especially during the spring, but due to causes other than wind erosion. This instability remains a significant barrier to the recolonization and restoration of abandoned milled surfaces. Further research is required on surface processes in milled peatlands throughout the year.

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