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Soil moisture, water tension, and water table relationships in a managed cutover bog

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Abstract

This study evaluates the hydrological conditions in a harvested bog where various water management schemes have been implemented to ameliorate conditions limiting *Sphagnum* regeneration. The study sites included a natural bog (natural), a recently drained and harvested bog (drained), which provided the hydrological extremes. Also included are a drained harvested bog with ditches blocked with (1) no other management (blocked), (2) peat bounded by open water at 5-m intervals (5-m), and (3) with straw mulch on the surface (mulch).

The study period from May to September 1995 was drier than normal. The water table in the drained site descended to −107 cm by late August, compared with −72.5 cm at the blocked site. Both the 5-m and mulch sites (ditches also blocked) had water table recessions similar to the natural site (minimum approx. −62 cm). In the drained and blocked sites, little variation in water table depth occurred after early July, suggesting water exchanges with the atmosphere occurred to and from the unsaturated zone only. Soil moisture in the upper 3 cm layer on the drained and blocked site were similar, in spite of greatly different water table depths, dropping below 20% by volume, compared with a minimum of 30% when mulch was used. Soil water tension profiles suggest most of this storage change occurred in the upper 30 cm. The water table depth, therefore, was not a good indicator of water availability at the surface.

Pressure head in the unsaturated zone (1 cm below the surface) in the drained and blocked sites was maintained between 0 and −100 cm (mb) 18 and 34% of the time, respectively, and with water management with open water (5-m) and mulch, increased to 55 and 97% of the time, respectively. The greatest tension, however, was observed on the blocked site (−355 cm), rather than the drained site (−247 cm), suggesting lower suitability for *Sphagnum* at the former. This was attributed to the higher bulk density (hence smaller pore structure) at the blocked site ($\rho_b = 92.1$ kg compared with 55.7 kg m^{-3}). Higher bulk density at the blocked site was ascribed to its longer time since disturbance. This implies restoration should begin as soon as possible after harvesting is finished. © 1997 Elsevier Science B.V.

Keywords: Soil moisture; Water tension; Water table relationships; Managed cutover bog

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1. Introduction

Peat production is an important industry in North America and Europe (Keys, 1992). Drainage and removal of layers of moss and peat alter the hydrological properties of exploited bogs. These conditions severely inhibit the re-establishment of *Sphagnum* mosses, the primary peat forming vegetation (Campeau and Rochefort, 1996). A better understanding of the hydrological processes which limit *Sphagnum* regeneration is required to restore the natural function of these systems after harvesting is abandoned.

Natural bogs have a loosely structured, fibric, and permeable upper layer of living and poorly decomposed mosses, called the acrotelm (Ingram, 1978). The water storage properties of the acrotelm stabilize the water table, and maintain it close to the surface—a requirement for the continued development of *Sphagnum* in the peat forming cycle (Clymo, 1983). Through drainage and harvesting, whereby the acrotelm is typically removed, the underlying denser, more decomposed peat is exposed, and undergoes further structural changes caused by oxidation, shrinkage, and compression (Schothorst, 1977). Price (1996) indicated that the specific yield of the catotelm decreased from about 0.2 to 0.05, 3 years following drainage and cutting. Consequently, water fluxes on cutover peat result in a widely fluctuating water table, which descends deep within the remaining peat profile during the drier summer months (Schouwenaars, 1993; Price, 1996). Schouwenaars (1988) suggested that the water table should not drop below 0.4 m for effective *Sphagnum* re-establishment on cutover bogs, but Price (1996) noted that the capillary pressure of the surface peat may be a more important consideration.

Sphagnum mosses are non-vascular plants. To avoid desiccation and death (Sagot and Rochefort, 1996), they are required to draw water from the soil by capillary action, at a rate greater that or equal to the atmospheric water flux from the plant. A *Sphagnum* carpet can be regenerated on a bare peat surface by laying plant fragments (diaspores) on the surface, under controlled climate and moisture (greenhouse) conditions (Campeau and Rochefort, 1996). While the amount of evaporation which occurs from individual plants (diaspores) is unknown, the evaporation from the bare peat of a cutover bog dries the soil, increasing the water tension therein. At some point the tension is too great for *Sphagnum* diaspores to tolerate, and they desiccate and die.

The rate of water rise into living and poorly decomposed *Sphagnum* by capillary processes is a function of its pore structure. This structure includes (1) intercellular spaces between stems and branches, and (2) intracellular spaces associated with the hyaline cells of the plant (Clymo and Hayward, 1982). Capillary water can be retained within the intracellular spaces when the water table is lowered the equivalent of −100 cm (−100 mb), having a corresponding moisture content of 10–20% (Hayward and Clymo, 1982). When plant material decomposes, as in the deeper (or cutover) peat the pore spaces decrease in size, and the water retention capacity increases (Okruszko, 1995). Boelter (1968) showed that for a capillary pressure equivalent to a water table depth of −100 cm, the water content of living *Sphagnum* carpets was about 10% by volume, compared with 70% in well decomposed peat. Thus since soil moisture on a (generally well decomposed) cutover peat surface can drop below 50% by volume (Price, 1996), high soil water tension may develop, and present very hostile conditions for *Sphagnum* development.

To ameliorate these conditions, various methods have been used. The primary step normally involves blocking active drainage ditches (Eggelsmann, 1988; Rowell, 1989). Price (1996) suggested this was inadequate in Quebec. Creation of open water (Beets, 1992; LaRose, 1996; Spieksma et al., 1996) increases water retention on site, and stabilizes the water through lateral seepage. The application of mulches has been shown to improve *Sphagnum* regeneration (Quinty and Rochefort, 1997). The above studies have established some basic knowledge about rewetting procedures, but an in depth understanding of the processes involved is required, if large scale restoration is to be done effectively and affordably. Strategies and approaches for bog restoration must take into consideration the hydrological conditions at the surface. Therefore, the objective of this study is (1) to understand the soil moisture–soil tension–water table relationships in peat, and (2) to evaluate their effect in an undisturbed bog, on an abandoned cutover bog, and in partly rewetted cutover bogs.

2. Study area

The study area was near Sainte-Margeurite-Marie, in the Lac Saint-Jean area of Quebec, Canada (48°47′N, 72°10′W). The average annual temperature is 1.7°C, with average January and July temperature of −17.1 and 17.3°C, respectively (Environment Canada, 1982). Mean annual total precipitation is 906 mm (32% falling as snow). Mean annual runoff in the nearby Mistassini River is 623 mm (Environment Canada, 1992).

The peatland is situated on a terrace of deltaic sands in the Lac Saint-Jean lowland (Morin, 1981), and is part of a 4315-ha bog-poor fen complex which can be classified as Plateau Bog (National Wetland Working Group, 1987). The peat deposit has developed over permeable sands because of a well developed iron pan which limits seepage losses (Price, 1996). This study examined a 'natural' portion of this bog, and several sections within cutover portion of the peatland.

Drainage operations began in 1990. The upper 0.35–0.6 m (acrotelm) was block-cut in 1991 with heavy machinery. Ditches (30-m spacing) were blocked in spring 1993, but were not back-filled. On this section of bog were three experimental areas, (1) a control site which in which ditches were blocked in spring 1993 but with no other management (blocked site), (2) a similar site but with a straw mulch (2250 kg ha^{-1}) applied over a 15 × 15-m plot (mulch site), and (3) a site in which there were four unconnected 20-m-long parallel ditch/reservoirs spaced 5 m apart, to increase the proportion of open water (5-m site) (LaRose, 1996). A second area was also studied, which was drained in 1993, and cut in the same way in 1994. Ditches were not blocked (drained site). All these sites are essentially devoid of vegetation.

The section of natural bog studied incorporated a transect perpendicular to a perimeter ditch surrounding the cutover section of the peatland. Data are reported from a well 200 m from the ditch. The surface cover of the natural bog is dominated by *Sphagnum fuscum*, *S. angustifolium*, *S. magellanicum*, and *S. capillifolium*. *Sphagnum* hummocks are typically 0.3 m above the *Sphagnum* lawn. There is a sparse cover of Larix laricina and Picea mariana.

3. Methods

The study was done between 6 May and 27 September 1995. Rain was measured with a tipping bucket rain gauge 0.5 m above the surface at two locations. Daily evapotranspiration from the natural and cutover surfaces was estimated with the combination model of Priestley and Taylor (1972), where

$$E=\alpha(s/(s+q))(Q^{*}-Q_{\mathrm{G}})/L\rho \qquad (1)$$

and where E is the evapotranspiration rate (mm day^{-1}), L is the latent heat of vaporization (J kg^{-1}), ρ is the density of water (kg m^{-3}), s is the slope of the saturation vapour pressure–temperature curve (Pa °C^{-1}), q is the psychrometric constant (0.0662 KPa °C^{-1} at 20°C), Q^{*} is the net radiation flux (J day^{-1}), and Q_{G} is the ground heat flux (J day^{-1}). When $\alpha = 1$, Eq. (1) represents equilibrium evaporation, which is the condition when there is no vapour pressure deficit in the near surface atmosphere. The ratio of actual and equilibrium evapotranspiration provides an empirical coefficient (α) which can be used in Eq. (1) to estimate evapotranspiration when direct measurements are unavailable, but when net radiation, ground heat flux, and air temperature are. The coefficient α was determined from Bowen ratio–energy balance measurements over natural and cutover peat at this site in 1993 (see Price, 1996). The average (±standard deviation) α for the natural and cutover site between 06:30 and 18:00 h was 1.21 ± 0.27 and 1.25 ± 0.16 for the natural and cutover sites, respectively. Net radiation was recorded with a radiometer 3.0 m over the peat surface. The ground heat flux was measured by two soil heat flux plates 0.5 cm below the peat surface. The air temperature was measured with a shielded thermocouple 1 m above the peat surface.

Water level was measured daily using wells which were of several designs. At the natural site, wells constructed of 50-mm ABS, slotted along their entire length, were used in a transect at 1, 5, 10, 15, 20, 45, 70, 120, and 200 m from a 2-m-deep perimeter ditch. At the blocked site, wells of the same design were organized in a transect perpendicular to a blocked ditch, at a distance of 1, 2, 5, 10, and 15 m from the ditch edge. At the mulch and drained site, 19-mm ABS pipes, slotted along their entire below ground length (1.2 m), were employed. A single well was used at the mulch site, but at the drained site, wells were placed at 0.5, 1, 2, 3.5, 5, 10, and 15 m from the ditch. Wells were covered with a geotextile screen.

Soil moisture and bulk density were determined gravimetrically, on samples retrieved with a cutter which sampled the upper 3 cm of soil. Three samples were taken daily at each of the drained site, blocked site, and mulch site, and returned to the lab. for analysis.

Matric tension was measured at the drained, blocked, 5-m and mulch sites. Tension was measured at −1, −3, and −7 cm with a 1-cm o.d. porous ceramic cup inserted horizontally into a pit wall, connected to a partially water filled L-shaped tube protruding above the peat surface. The pit was backfilled with peat. Pressure was measured with a Tensimeter™ pressure transducer accurate to ±1 mb, and adjusted to account for the height of the water column above the ceramic cup. Tension at −10, −20, −30, −40, and −50 cm was measured with multi-level tensiometers (SoilMoisture Corp.), which consist of ceramic disks connected to mercury manometers. Values herein are expressed in cm of water (1 cm ≈ 1 mb).

4. Results

Monthly temperature and total precipitation at nearby Peribonca, for May, June, July, August, and September deviated from the long term normals (1951–1980) by 0.7, 1.3, 2.7, 3.3, and –0.3 °C, and +36.5, –46.0, –56.7, –47.6, and –23.2 mm, respectively (Environment Canada, 1982; Sommaire Climatologique du Quebec, 1995). Rainfall occurred in small isolated events between mid-June and mid-August, after which frequency and magnitude increased (Fig. 1). Evaporation averaged 3.1 mm day^{-1}, and ranged from 0.14 to 5.8 mm day^{-1} (Fig. 1).

Water table depth below the surface peaked about 23 May. At all sites except the drained site, the water table was essentially at the surface (Fig. 2). At the drained site, the peak water table elevation was at 40 cm below the surface. The water table in the drained site descended to –107 cm by late August, compared with –72.5 cm at the blocked site. Both the 5-m and mulch sites (ditches also blocked) had water table recessions similar to the natural site (minimum approx. –62 cm). During May and June, when water tables were generally high, there was marked variation in response to wetting and drying events

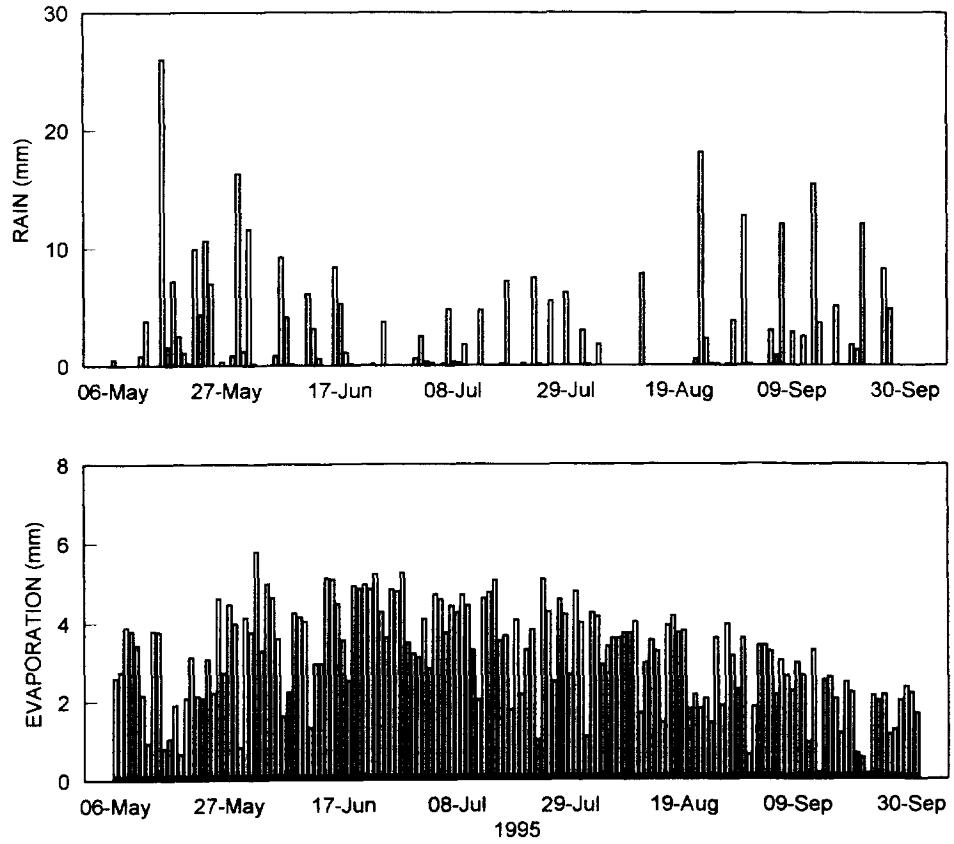

Fig. 1. Rain and evaporation for the study period.

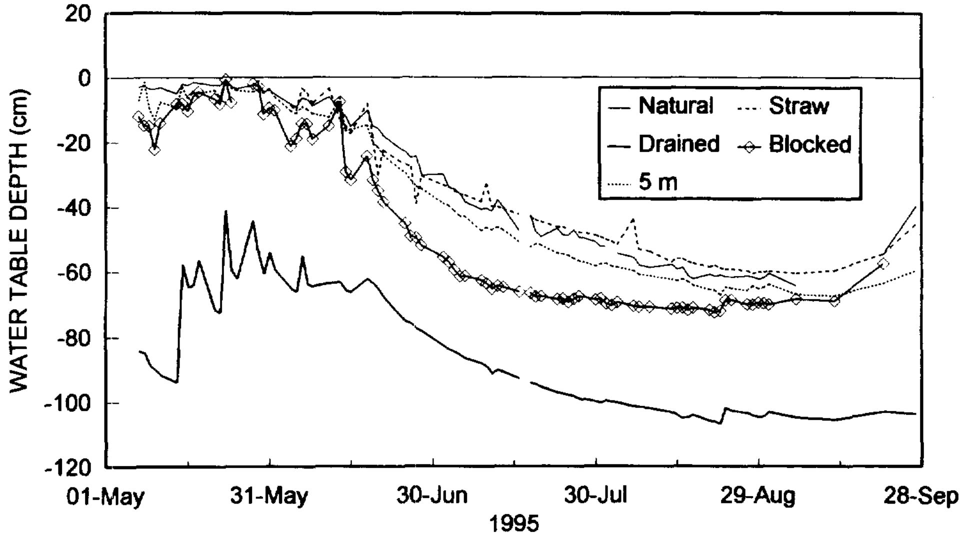

Fig. 2. Water table depth below the peat surface.

at the drained and blocked sites. As the water tables descended over the summer, remarkably little short term variation was observed at these two locations.

Volumetric soil moisture in the upper 3-cm layer was lowest on the drained site (Fig. 3). At the blocked site, soil moisture was about 10% higher during May and June, but thereafter was close to that in the drained site, dropping below 20% by volume by mid-August. In contrast, soil moisture was held above 30% when mulch was used (Fig. 3). There are no data for the natural or 5-m sites. Soil moisture was related to water table position. However, the near zero slope (in Fig. 4) when the water table was low indicates

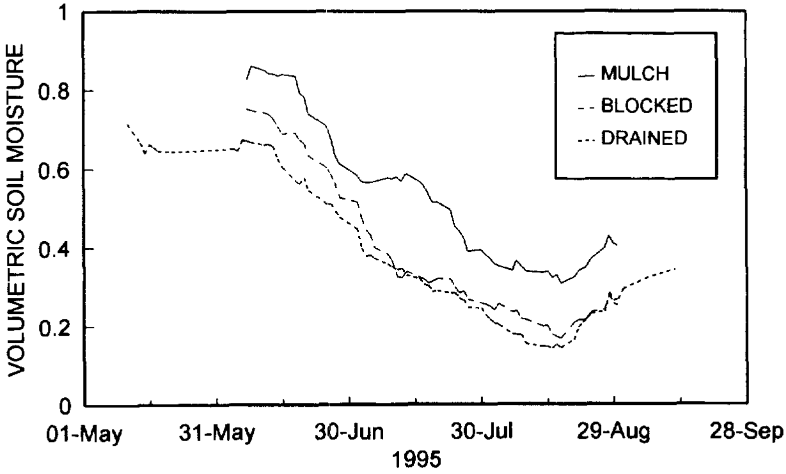

Fig. 3. Volumetric soil moisture in the 0–3-cm soil layer. Data shown are 7-day moving averages.

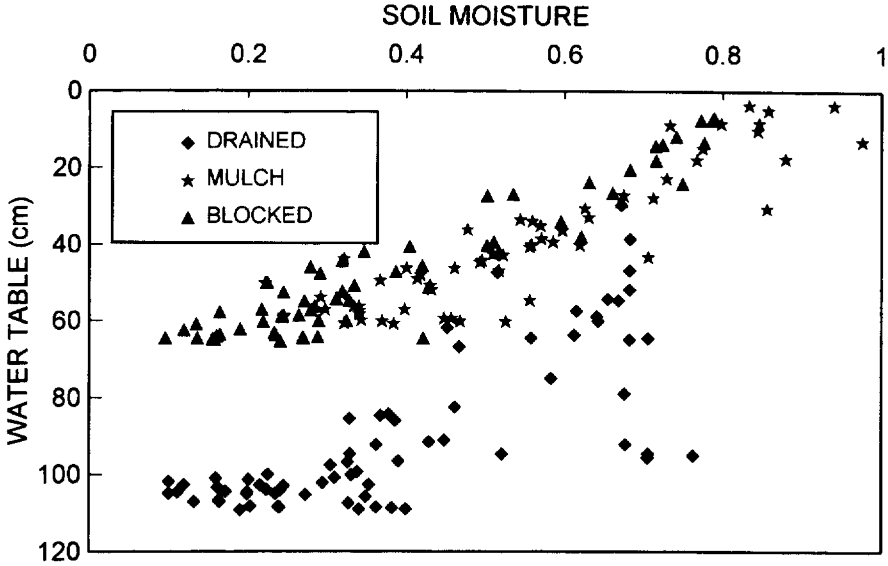

Fig. 4. Soil moisture in the 0–3-cm layer versus water table depth below the surface.

little relationship between water table and soil moisture during drier periods. Note also that the relationship for the drained site was different from the blocked and mulch sites (Fig. 4).

Soil samples used to determine soil moisture were also used to calculate bulk density. Bulk density of the peat matrix (0–3 cm) was not constant over the season, nor from site to site. Bulk density at the drained site was lowest (of the cutover peat), (averaging 55.7 ± 11.1 kg m^{-3}), compared with that at the blocked and mulch sites (92.1 ± 10.7 and 81.7 ± 11.2 kg m^{-3}, respectively). The peaks in bulk density corresponded with the drier periods.

Tension head, measured at −1 cm below the surface, displayed a similar seasonal trend to water table and soil moisture, being highest in May (smallest negative number), lowest in mid-August (Fig. 5). During May and June, the tension was greatest at the drained site, and lowest at the mulch site. The low tensions at the mulch and 5-m sites persisted over the summer. However, there was a reversal during July and August, whereby the tension at the blocked site became much greater (more negative) than at the drained site. Vertical profiles of tension head (expressed as total head relative to the local ground surface) during a wetter period (Fig. 6(a)) have relatively small vertical gradients, and the magnitude of tension is greatest at the drained site, and progressively smaller at the blocked, 5-m and mulch sites. Following a long dry period in August, only a small decrease in tension occurred at depths greater than 30 cm below the surface (Fig. 6(b)), except for at the drained site, where the water table was still declining. In contrast, the soil tension near the surface at all sites increased substantially. However, the largest increase was at the blocked site, which far surpassed that at the drained site. Soil moisture was related to soil water tension in non-linear fashion, typical of these relationships (Fig. 7).

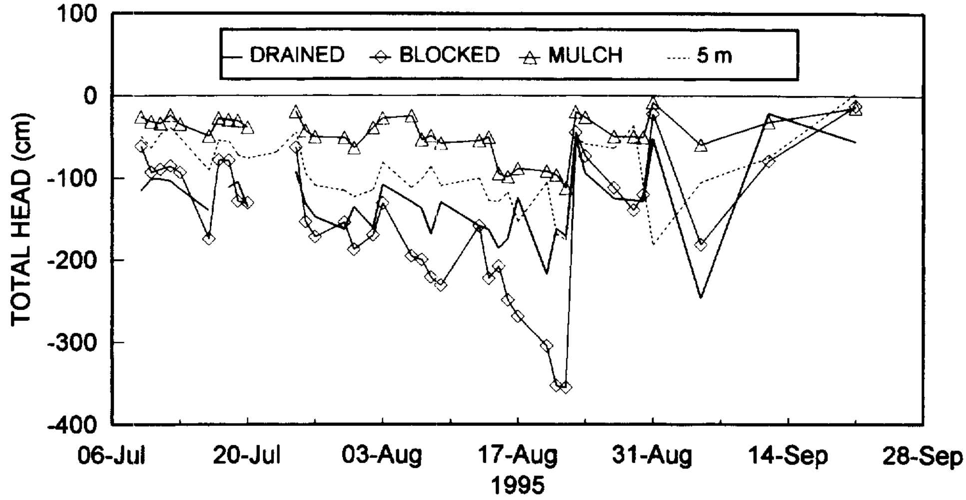

Fig. 5. Water tension expressed at total head relative to the surface, measured 1 cm below the surface. Note that 1 cm of tension is equivalent to 1 mb.

5. Discussion

The 1995 study period was drier and warmer than normal, thus provided an opportunity to examine the limiting environmental conditions for *Sphagnum* re-establishment. The water table in the natural site decreased to −65.3 cm in August. This is much lower than the −15 cm observed in a nearby bog in 1993 (Price, 1996), and in 1994 (Price, unpublished data, 1994). There was not a monotonic decline in the water table along the transect toward the ditch 200 m away, thus the presence of the ditch probably did not have a significant effect on the well at this location (see Boelter, 1972). At the blocked site, the minimum

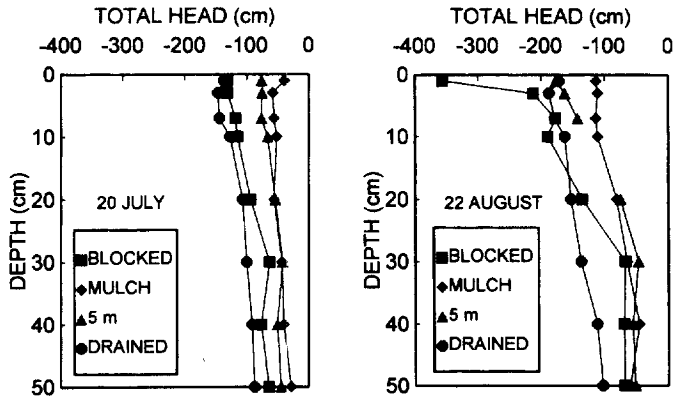

Fig. 6. Water tension profiles expressed as total head relative to the surface, measured at 1, 3, 7, 10, 20, 30, 40, and 50 cm below the surface.

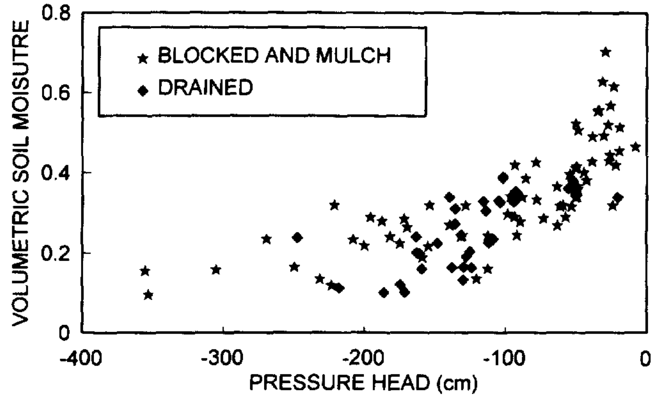

Fig. 7. Soil moisture-tension characteristic curve for the 0-3-cm soil layer.

water table levels were –72.5 cm, compared with –60 cm at the same site in 1993 (Price, 1996). The decline in the water table there, which occurred throughout May, June, and July, did not persist into the dry month of August (Fig. 2). Since drainage is minimal at this site (Price, 1996), and the water deficit ($P - E$) in August was 40.6 mm, the steady water table indicates that atmospheric the water demand was supplied entirely from the unsaturated zone. Furthermore, this loss occurred principally from the upper 30-cm layer, as suggested by the soil water tension profiles (Fig. 6). At the drained site, short term water table variation was also minor throughout July and August, although the general decline persisted into September, an indication of continued seepage into the active drains (ditches). As with the blocked site, water losses by evaporation, and water gains during rain events, were accounted for by exchanges entirely within the unsaturated zone. This explains the low sensitivity between soil moisture and water table position (Fig. 4), when the water table was low. The decoupling of the atmospheric processes from the phreatic zone caused a steady decline in soil moisture, particularly near the surface (Fig. 3).

The water table trend at the 5-m and mulch sites differed little from that at the natural site (Fig. 2), which suggests that these management tools are effective in retaining water at the site. The short term fluctuations, which occurred throughout the duration of the study, indicate that rain water percolated to the water table, and evaporative losses came partly from the phreatic zone. This was possible because of the higher soil moisture content, which allowed water to move more freely in the unsaturated zone. The implications for *Sphagnum* re-establishment are that *Sphagnum* diaspores introduced to the surface (Campeau and Rochefort, 1996) have greater access to soil water, thus have a better chance of surviving.

Soil moisture at the surface was positively related to water table elevation, as expected (Fig. 4). This relationship, however, was not consistent from site to site. At the drained site, the deep water table did not result in a lower range of soil moisture (Fig. 3), nor did it produce the extreme water tensions (Fig. 6). Thus the water table elevation was not a good indicator of hydrological conditions at the surface. The explanation for this can be found in the soil moisture-pressure characteristic curve (Fig. 7). Note from Fig. 7 that a soil water tension of about –200 cm at the drained site corresponds to a soil moisture of approximately 0.2. At the blocked (and mulch site), a soil water tension of about –350 cm was associated with the same moisture content. Obviously, the nature of the peat is very different at these locations. This was previously noted—the bulk density of the peat at the drained site was considerably less than at the blocked (and mulch) site. Peat with a higher bulk density has much greater soil water retention (Boelter, 1968). Therefore, water lost from the surface by strong evaporative forces resulted in a strong water tension in the denser peat at the blocked site, where it was unprotected by a mulch. The difference in bulk density, hence water storage properties, is a function of time since drainage operations began (1990 in the blocked and mulch sites, 1993 in the drained site). The longer period of disturbance at the blocked (and mulch) site has permitted more peat subsidence and oxidation (Schothorst, 1977). Possible differences in vehicular traffic during harvesting, may also be a factor.

Schouwenaars (1988) suggested that for effective restoration of cutover bogs, the water table is required to be less than 40 cm from the surface. This degree of rewetting was not achieved in this study, nor in previous years of study at this site (LaRose, 1996; Price, 1996). For this study period, the water table was above this level for <1, 39, 46, 53, and 54% of time at the drained, blocked, 5-m, mulch, and natural sites, respectively. The continental location of this study contrasts with the more maritime European setting on which Schouwenaars's data was based. In any case, this study shows that the water table is not a good indicator of the hydrological condition of the surface of the bog.

The surface condition can only be evaluated by direct measurements of soil moisture or soil water tension. These conditions need to be evaluated on the basis of survival thresholds of the *Sphagnum* mosses, and an understanding of the water limitations imposed by the system. The soil moisture–water tension relationship (Fig. 7) indicates that capillary saturation occurred at tensions above −30 cm, and that soil water migrated readily out of the soil at tensions down to about −100 cm, corresponding to a volumetric soil moisture of about 0.2. Beyond this level, there was little further change in the soil moisture content of the peat. Only the mulch and 5-m sites maintained soil water tension above −100 cm for a significant proportion of the study period (Fig. 5).

The soil moisture and water tension thresholds critical to the survival of *Sphagnum* diaspores introduced to the surface are currently unknown. The primary issue is the availability of water to prevent desiccation of the *Sphagnum* plants (Sagot and Rochefort, 1996). It is water stored within the unsaturated zone which controls water availability at the surface. The soil moisture and soil water tension data indicate the unsaturated zone provided a substantial quantity of water to meet the atmospheric demand. Consequently, however, the high water tension in the surface layer may exceed the ability of the *Sphagnum* diaspores to draw water from the soil, since this must be done by the capillarity they can generate within their own (non-vascular) tissue. Preliminary field results (Rochefort, L., unpublished data, 1994, 1995), suggest the drained and blocked sites regularly exceed these critical thresholds, since they do not support *Sphagnum* regeneration, whereas the 5-m and mulch site are probably within the limit.

6. Conclusions

From the above results and discussion, it is concluded that the recovery of the water table achieved through various water management strategies indicate in a relative sense, the success of rewetting strategies. Abandoned cutover areas, where no remedial measures have been made (drained site), had a hydrological regime most different from the natural site. Simply blocking drainage ditches (blocked site) caused good water table recovery during the wetter spring period, but the water table recession was much faster and greater than in a natural area. More aggressive water management techniques, like creating open water reservoirs and using straw mulch, in addition to blocking ditches, recreated a water table regime comparable to that in the natural area.

Evaluation of the surface soil moisture data indicate that simply blocking ditches did not ameliorate the surface condition except during spring. The more aggressive remedial measures were required. Applying a straw mulch increased the surface soil moisture by 10–15%, compared with the untreated areas. Soil moisture was related to water table depth, but only when the water table was relatively high, as during springtime. This relationship was not constant over space.

Water tension was significantly decreased adjacent to open water (5-m site) and mulch site. Tension at these locations was maintained above −100 cm (−100 mb) 55 and 97% of the time, respectively, thus making water available to *Sphagnum* diaspores, through capillary suction generated within pores associated with their hyaline cells. In contrast, the drained and blocked sites had tensions above −100 cm only 18 and 34% of time, respectively. This demonstrates their unsuitability to *Sphagnum* survival. The data also indicate that greater tension occurred where the peat is denser (more decomposed). The implication for this is that restoration should begin as soon as possible after abandonment.

Acknowledgements

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