Science of the Total Environment 505 (2015) 573–586

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Landscape analysis of nutrient-enriched margins (lagg) in ombrotrophic peatlands

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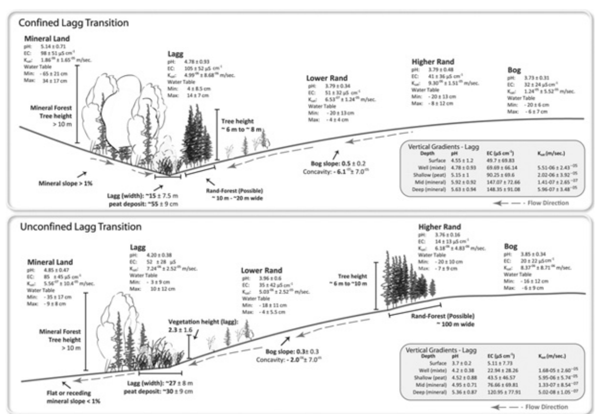
HIGHLIGHTS

- Hydraulic, hydrochemical, geomorphic, and vegetation gradients characterize laggs.
- Lagg morphology can be categorized as confined or unconfined.
- Lagg water quality and variability are intermediate between bog and mineral terrain.
- Laggs are an integral part of the peatland, and contribute to ecosystem function.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 10 September 2014
Received in revised form 1 October 2014
Accepted 1 October 2014
Available online 23 October 2014

Edited by: F. Riget

Keywords:
Lagg
Ecotone
Bog
LiDAR
Ecohydrology
Geomorphology

ABSTRACT

Scientific knowledge of the wet zone – the lagg – that tends to form at the edge of ombrotrophic peatlands is surprisingly limited. In this study, we aim to improve the understanding of the ecohydrological functions of this transition by describing the form and abiotic controls of the laggs and margins of bog peatlands. Data collected in wells and piezometers along 10 transects (within 6 bogs), of the New Brunswick Eastern Lowlands are used to analyse the hydraulic and hydrochemical gradients, while airborne LiDAR data provides new insight on the geomorphology and the vegetation patterns of the bog–lagg–mineral transition zone. Based on their geomorphic character, the study transects are placed into 2 categories: confined and unconfined. Laggs of confined transition are found in a topographic depression, between the bog and a mineral slope >1%, while laggs of unconfined transitions are adjacent to a flat (≤1%) or receding mineral slope (sloping away from the lagg). Water level (4 ± 9 cm vs. −3 ± 9 cm), pH (4.8 ± 0.9 vs. 4.2 ± 0.4), electrical conductivity (EC_{corr}) (105 ± 52 μS cm^{-1} vs. 52 ± 28 μS cm^{-1}) and peat depth (55 ± 9 cm vs. 30 ± 9 cm) are found to be higher, respectively, for the confined laggs than for the unconfined. Saturated hydraulic conductivity (K_{sat}) of the lagg's upper peat layer resembles that of bog environments, but quickly reduces with depth, impeding vertical water flow. The greatest abiotic control of the lagg appears to be topography, which affects water flow rates and direction, thus water chemistry, nutrient transport and availability, hence vegetation characteristics. Our results suggest that the features of the

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http://dx.doi.org/10.1016/j.scitotenv.2014.10.007

transition zone that include the lagg, influence the quantity and variability of water within the adjacent peatland, and should be considered as integral part of the peatland complex.

1. Introduction

"Lagg" refers to the transitional zone that forms at the margin of natural ombrotrophic peatlands; some are distinct and others are not. In its hydrology and hydrochemistry, it takes on qualities of both the bog and the adjacent mineral terrain (Whitfield et al., 2006). As acidic water from the bog meets mineral-enriched waters from surrounding environments, rapid ecohydrological changes occur over short distances (Howie et al., 2009; Paradis et al., 2014). This can easily be observed in the vegetation (Damman, 1986; Paradis et al., 2014), which transitions from dominantly *Sphagnum* mosses in the bog centre, to shrubs, then trees in the neighbouring mineral forest. The lagg plays three key functions in a raised bog ecosystem: 1) high water levels in this zone reduces the hydraulic gradient in the margin of the adjacent bog, which helps the bog retain water (Schouwenaars, 1995); 2) during wet periods the lagg can efficiently move excess water away from the system (Godwin and Conway, 1939); and 3) it plays a role in the bog growth and expansion by impeding lateral expansion thus promoting vertical growth of the peatland (Godwin and Conway, 1939; Hobbs, 1986; Damman, 1986). Groundwater exchanges through the lagg zone affect water quality within and beyond the margin of the bog in both directions (Keough and Pippen, 1984), although their capacity to attenuate non-point-source water pollution (e.g. Zeng et al., 2012) is not known.

Laggs are not commonly recognized as an integral part of the peatland complex. Due to this lack of recognition, adjacent land-uses often encroach on laggs (Pellerin and Lavoie, 2003; Pellerin et al., 2008; Howie and Meerveld, 2013), or they are drained or otherwise damaged in peat harvesting, resource extraction operations or urban development. Little attention has been paid to their restoration and management, in part because their hydrological and ecological functions have not been well described, and remain poorly understood (Whitfield et al., 2006; Howie et al., 2009; Howie and Meerveld, 2013; Howie and van Meerveld, 2011). This lack of knowledge and understanding compromises the ability of land managers, who must make decisions without a clear understanding of the impact of developing within the margin, or in peripheral areas of bog peatlands (Murphy et al., 2007).

In Canada, most of the research on lagg function comes from the study of a large urban peatland: Burns Bog (Vancouver, British Columbia) – which has lost much of its natural lagg to anthropogenic disturbances and land use changes – and other costal bogs through the work of Hebda et al. (2000), Whitfield et al. (2006), and Howie et al. (2009, 2013). After several decades of restoration efforts, researchers are recognizing that for a raised bog to be viable and maintain its integrity, lagg zones must be present and functioning (Hebda et al., 2000). Whitfield et al. (2006) conceptualized the lagg structures that might have existed prior to the disturbance of Burns Bog. They identified 4 forms of transition from peatland to mineral terrain likely to have occurred at different locations around the peatland: 1) between the bog and a relatively steep mineral slope, 2) confined between a natural river levee and the bog, and subject to occasional flooding from the nearby river, 3) spreading across an ancient beach formation, and 4) in an area assumed to have been dominated by natural discharge from the bog across a flat deltaic terrain (Whitfield et al., 2006; Howie et al., 2009). Whitfield's model was later refined by Howie et al. (2009), using historical aerial photography and stereography to hindcast the historical location of the lagg, based on vegetation height. This latter model includes predictions of the expected presence of 4 ecological gradients for the bog–lagg–mineral terrain transition where 1) the height of the vegetation is expected to increase from bog to lagg and mineral forest, 2) the hydrological gradient is presumed to be steeper on the upland side (relatively steep mineral slope) compared to the bog side, 3) the chemical gradient is suspected to have higher concentration in the mineral soil and gradually decreasing towards the bog, and 4) the soil permeability is expected to be lower in the catotelmic bog peat than in the mineral land.

The presence and the character of the lagg vary within and between peatlands, and its lateral and longitudinal extents remain a challenge to define (Paradis et al., 2014). This is true within a single geographical region and it becomes more problematic to generalize for different climatic, hydrogeomorphic and ecological regions. Consequently, this has resulted in inconsistent terminology and/or definitions for this zone, which has variously been referred to as marginal ditch (Rigg, 1925; Rigg et al., 1927; Rigg and Richardson, 1938), marginal fen (Conway, 1949), wet margin (Hobbs, 1986), lagg fen (Bragg, 2002; Rydin and Jeglum, 2006), lagg stream (Millington, 1954) and lagg (Couillard and Grondin, 1986; Payette and Rochefort, 2001; Whitfield et al., 2006; Howie et al., 2009,2013; Richardson et al., 2010; Howie and van Meerveld, 2011). Among the few studies specifically focussed on laggs (Blackwell, 1992; Smith et al., 1999; Howie et al., 2009), few have studied truly undisturbed ecosystems (e.g. Mieczan et al., 2012).

The impact of the landscape on the formation and functioning of the lagg has been mentioned by many authors (Godwin and Conway, 1939; Damman, 1986; Hebda et al., 2000; Whitfield et al., 2006; Howie et al., 2009; Howie and Meerveld, 2013), but few (Richardson et al., 2010) have quantified its geomorphology. The lagg is hydrologic in nature, and influenced by both the bog and the adjacent mineral land. To understand the landscape processes that control the form and functions of the lagg, its neighbouring ecosystems also need to be examined (Howie et al., 2009; Howie and Meerveld, 2013; Paradis et al., 2014). Based on the conceptual model of Whitfield et al. (2006) and Howie et al. (2009), our goals are 1) to describe the form and abiotic controls of the transition from *Sphagnum* dominated bog ecosystem to the surrounding mineral forest and, 2), to suggest a conceptual model of the "bog–lagg–mineral land" transition for the Canadian Atlantic provinces.

2. Study area

All study sites were part of the New Brunswick Eastern Lowlands, located between the town of Bertrand (47°45′N, 65°03′W), and the eastern limit of Miscou Island (47°59′N, 64°31′W) (Fig. 1). The region is characterized by a cool, moist climate, with 4 months below freezing (Canadian Climate Normals 1971–2000, Bathurst, NB). Mean annual temperature in the region is 4 ± 1 °C, and mean annual precipitation is 1059 mm (30% as snowfall) (Canadian Climate Normals 1971–2000, Bathurst, NB). The growing season of 2011 – the study period – was particularly wet with an average May–September precipitation of 617 ± 10 mm compared to the 435 mm average for normal years (Canadian Climate Normals 1971–2000, Bathurst NB). The peninsula is underlain by red and grey sandstone, interbedded with mudstone and conglomerate, which combined with the flat topography (ranging from 0 m to ~45 m above sea level (MASL) for the region studied), often results in poor drainage (Colpitts et al., 1995). Consequently, organic soils have developed in many of the regional glacial depressions, and nearly half of New Brunswick wetlands are found in the eastern lowlands (Zelazny, 2007).

In June 2011, 6 relatively undisturbed ombrotrophic peatlands of various sizes (between 31 and 1500 ha) were instrumented with a total of 10 transects comprising wells and piezometers, straddling the bog and the adjacent mineral land (Table 1). Each of these was selected to cover lagg transitions ranging from wet and well defined, to dryer and more diffuse. These ecotones were identified mainly based on the

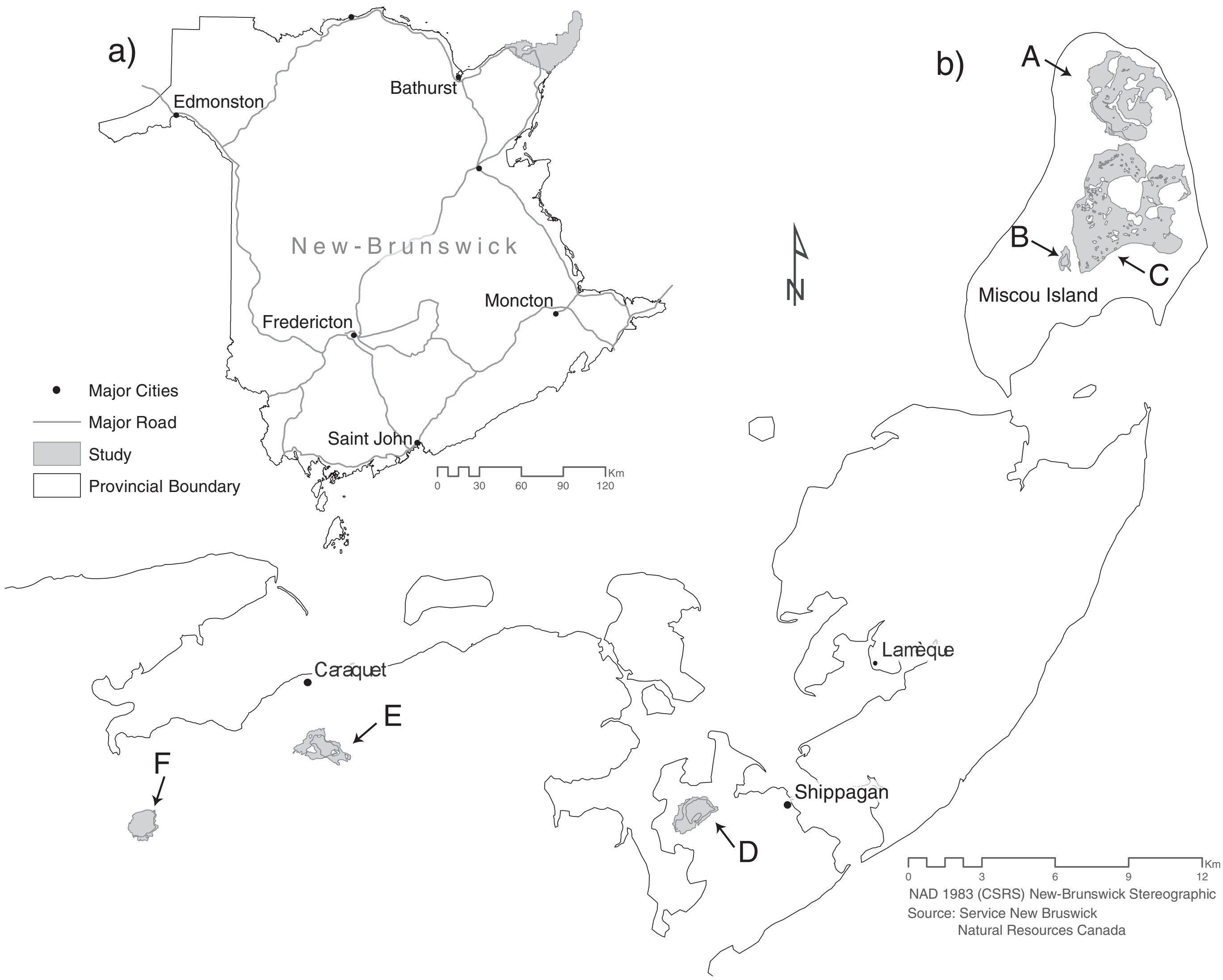


Fig. 1. Study sites. a) All six study sites were located within the lowlands of north eastern New Brunswick. b) The capital letters indicate each of the individual study sites, located between the town of Bertrand near Caraquet, and the eastern limit of Miscou Island.

presence of transitional vegetation (e.g. *Alnus incana* ssp. *rugosa*, *Ilex* (*Nemopanthus*) *mucronatus*, *Rhododendron canadense*, *Viburnum nudum* ssp. *cassinoides*), near or above ground water table (late May), surface water chemistry (higher values in relation to adjacent peatland) and the presence of peat.

The transects can be categorized as having 5 landscape units: 1) mineral land, 2) lagg (as described above), 3) lower rand, 4) upper rand, and 5) bog. The mineral land units were forested (mixed) with no peaty soil. The rand can be described as the sloping margin of a raised bog (Godwin and Conway, 1939; Damman, 1986; Hebda et al., 2000; Wheeler and Shaw, 1995; Howie and van Meerveld, 2011), found between the dome and the lagg, towards the edge of the peatland. The rand occurs where the hydraulic gradient of the bog steepens at the edge of the dome, resulting in lower water tables that promote the growth of woody vegetation including shrubs and small trees. The terms "upper" rand and "lower" rand are also utilized to describe the sections of the

Table 1
Study sites. In 2011 6 peatlands (A to F) were instrumented with a total of 10 transects (A1 to F1). Peatland sizes varied between 31 and 1500 ha, and transect length between 76 m and 673 m.

Site (peatland)	Northing	Westing	ha	Elevation (MASL)	Peat depth max (m)	Transect name	Length (m)
A	47°59′41″	64°31′30″	619	4	5	A1	210
B	47°56′18″	64°32′41″	31	9.2	1.5	B1	104
C	47°56′05″	64°31′55″	1500	8.2	5.5	C1	102
						C2	179
						C3	222
D	47°44′25″	64°45′08″	160	4	2.9	D1	673
						D3	550
E	47°45′58″	64°57′29″	148	19.8	4	E2	76
						E3	199
F	47°44′33″	64°03′21″	114	27.3	5.5	F1	246

rand that are respectively, closer to the central bog dome and to the edge of the peatland (Godwin and Conway, 1939; Boatman et al., 1981; Howie and van Meerveld, 2011). Finally, the bog unit can be described as *Sphagnum* dominated and above the sloping margin.

3. Methods

For each of the 10 transects, wells were installed across the transition zone in each of the 5 landscape units described above. For the majority of our sites, a thick band of trees dominated by black spruces (*Picea mariana*) grew within the rand, at times closer to the bog centre (higher rand), and other closer to the lagg (lower rand). The wells of the lower and higher rand are therefore comparable (between sites) in terms of their relative geographical position, but not in terms of vegetation. Wells were generally ~120 cm in length, ~95 cm of which was slotted, and placed below the ground surface. In the lagg, however, shallow peat and high water levels (often above ground) necessitated both shallower wells (~65 cm of open pipe) and a longer stick-up. A nest of 3 piezometers (20 cm slotted intake) was also installed in the centre of each lagg. Absolute piezometer depth differed for each site, but all had a shallow piezometer centred ~10 cm above the mineral layer, a second one centred ~10 cm below the peat–mineral interface, and a deeper one at refusal, or as deep as the equipment allowed (between ~150 and ~190 cm below ground). Wells, shallow and mid-depth piezometers were 3.2 cm inner diameter ABS pipes. However, because of the nature of the mineral soils and its suspected lower hydraulic conductivity (K_{sat}), smaller 2.5 cm PVC pipes, were used for the deepest piezometers, to minimize the response time. All wells and piezometers were covered with screens along the slotted section.

Each instrument was measured weekly between July 4th and August 23rd, 2011 (some exceptions), and once at the end of October, 2011. After measuring hydraulic head, wells and piezometers were purged and allowed to recover (some only partially)and then electrical conductivity (EC), pH and temperature were measured with a portable EC and pH meter (pH accuracy: 0.05). In a costal bog environment, most of the EC is driven by H ions and therefore the field measurement for EC needs to be corrected for H^+. Popular correction methods such as the one suggested by Sjörs (1950) rely on the concurrent measured pH values. For accurate measurement of pH in low EC waters, low ionic strength buffers and high accuracy electrodes are preferred. To gain confidence in our field measurements, we performed an error analysis using the portable instrument and buffer solutions that were used in the field (measured), and instruments with higher precision (pH: 0.001) and low ionic strength buffer (standard). We tested 10 water samples composed of different ratios of bog/tap water (in 10% increments), and compared the measurements (average of 10 measurements at ~1 minute interval per samples). The resulting correction curves indicated that the EC field values were acceptable ($R^2_{linear} = 0.999$), but that a correction was needed for the pH values ($R^2_{linear} = 0.966$). The field instrument used with regular ionic strength buffers had a tendency to overestimate pH values for solution ≤ 5.5, and to underestimate for solution > 6.0. After calculating the correction factors (CF = standard / measured) values were forecast between each of the 10 individual calibration points (linear regression). This allowed for the pH values to be corrected, and for the H^+ correction to be applied (EC_{corr}). The formula developed by Sjörs (1950), as presented in Rydin and Jeglum (2006), was used for this correction.

Saturated hydraulic conductivity (K_{sat}) was measured in wells and piezometers 4 times over the summer in both wet and dry conditions, using bail tests (Hvorslev and Waterways Experiment Station, U.S., 1951). For transect E3 however, slug tests (Hvorslev and Waterways Experiment Station, U.S., 1951) were necessary in some occasions (fast rise) for the bog and for the lagg shallow piezometer. The K_{sat} used for analysis is the geometric mean result of these 4 tests for each instrument.

Three horizontal gradients were evaluated at each site; water table, pH and EC were monitored from the wells placed in each landscape unit. In the lagg, wells were placed below the peat surface. However, in laggs where water levels were high (>~25 cm above the peat surface) at the time of installation (early June), the peat was often "swollen" making the boundary between the standing water and the peat surface difficult to determine. We later realized that with dropping water levels following the spring peak, the peat in very wet laggs subsided, leaving part of the slotted section of pipe in the standing water, and in one instance, above it (open air). Consequently, the hydrochemical data (pH and EC) analysed for the lagg horizontal gradient is a mixture of surface, organic and mineral water, which we deemed representative of the water available in the lagg. For this same reason however, we could not use the K_{sat} values recorded in the lagg wells, and used the shallow piezometer values (centred ~10 cm above the mineral interface), which are representative of the organic soil only.

Between August 23rd and 25th, 2011, 5 (C1, D1, D3, E2, F1, see Table 1) of the 10 laggs' surface water, well, and piezometers (3) were sampled (25 samples total). Pipes were purged before the collection of the samples and the tube used to pump the water was rinsed twice with distilled water before each use. The samples were filtered within 24 h (0.45 μm), and acidified with a 1% HNO_3 solution (1 ml of diluted solution in a 45 ml sample) for transportation and preservation. Samples were analysed within 4 months of collection with a Dionex chromatography system (ICS-3000) for their ionic composition (Ca, Na, K, Cl, Mg).

To evaluate the topographic gradients and vegetation height of the bog–lagg–mineral terrain transition, the Department of Natural Resources of New Brunswick (NBDNR) provided airborne LiDAR (Light Detection And Ranging) data. This was acquired by Leading Edge Geomatic Ltd. on November 4th 2009, at an altitude of 1600 m (system: Optech 3100 ALTM), with an accuracy of ± 0.15 m vertically, and ± 0.8 m horizontally (95% confidence). Although collected almost 2 years prior, the LiDAR data were considered representative of the sites studied at the time of the field survey; based on the rate of growth of the vegetation in bog peatlands, and the stability of the sites (no anthropogenic disturbances), landscape differences would have been negligible. A Differential Global Positioning System (DGPS) survey of the pipe top elevation was completed during the fall visit, when deciduous trees in the lagg and mineral forest had shed their leaves, for better satellite signal strength. A Leica Viva GNSS (Global Navigation Satellite System) with a sub-centimetre vertical accuracy was used in conjunction with Real Time Kinematic (RTK), placed over monuments tied to the Provincial High Precision Network (HPN). The survey was carried out in a known coordinate system (NAD83 CSRS New Brunswick Stereographic) to be used with the LiDAR data.

3.1. Data analysis

The LiDAR data were classified by the provider into ground, low vegetation, mid-vegetation and high vegetation. These classes were manually verified for each site and points were reclassified or removed if necessary. Point spacing across the sites (0.80 ± 0.03 m) allowed for the creation of high resolution (1×1 m) Digital Elevation Models (DEMs) and Digital Surface Models (DSMs) using an inverse distance weighted method with a low power (optimized for lower Root Mean Square Error (RMSE) by the geostatistical analyst in ArcGIS 10.1), with a minimum of 4 and a maximum of 6 neighbours (to avoid for excessive spatial aggregation). These surfaces were used to derive a third surface of the vegetation's residual elevations (DSM–DEM).

For each of the 10 transects, spatial patterns for vegetation heights (residuals) in cross-section (10 m buffer strips) were analysed with a running average moving window (Fortin and Dale, 2005). The window size was kept small (4 m) with a 2 m increment (n = 40/windows), with the intention to characterize the changes in vegetation heights approaching the lagg, which are themselves relatively narrow (from

~10 m to ~70 m for our study sites). To analyse the general topography and derived attributes, 10 m buffer strips of LiDAR data in point cloud (as opposed to interpolated surface) were extracted, spanning beyond the length of individual transects to include the local maximum elevation on each side of the lagg (transect length: 120 m to ~700 m). A quadratic polynomial regression was fitted to the ground returns to yield information about the slope and concavity of the terrain between the lagg and the local maxima on either side of it (bog and mineral land). To make it easier to compare results between the transects, the LiDAR ground elevation value at the location of the lagg wells was considered as base elevation and given a value of zero. The original lagg elevation was then subtracted from all data points, residuals were kept for analysis. The DEM and DSM models were created using ESRI ArcGIS 10.1 geostatistical analyst, the running average and morphometric analysis were carried out with the open source R statistical software (http://cran.r-project.org).

One way analysis of variance (ANOVA) was used on the data collected in the wells and piezometers to determine whether or not the landscape units could be considered as separate entities, or if it would be beneficial to group similar units (e.g. should the rand be divided into two units or analysed as one?). Subsequently, the analysis was repeated for data recorded at different depths in the lagg (peat, interface and mineral), to explore similarities and differences in the water chemistry of the different soils. Data were log-transformed to comply with the normality assumption of the parametric test, but did not consistently respect assumptions concerning the equality of variance. Therefore, when the null hypothesis was rejected, Fisher's Least Significant Difference (LSD) test was performed to compare the group treatment means and assess significance of differences between those groups. All analyses were completed with R statistical software, using the Basic and Agricolae packages.

The hydraulic gradient and specific discharge (q) were calculated using Darcy's Law (Freeze and Cherry, 1979) to assess the gradient and fluxes of water between adjacent landscape units (horizontal), and between the different depths within the lagg (vertical). Estimates for the lagg lateral fluxes were calculated from lower rand to lagg, and from mineral terrain to lagg, using the K_{sat} of, respectively, the lower rand and mineral land. A negative specific discharge (q) should be interpreted as lateral water influx to the lagg. The vertical flux was calculated from higher to lower screens, starting with the wells (from well to shallow piezometer, shallow to mid-depth, and mid-depth to deep): a negative gradient indicates upward flux.

4. Results

4.1. Topographic gradient — two types of transitions

The slope of the mineral land ranged from −1.5% to 6.7%, with 6 out of 10 transects above average (1.8% ± 2.2%; Fig. 2a, b, c, d, g, h). The remaining 4 transects had a mineral slope below average, 3 of them sloping away from the lagg (negative slope: −0.2 to −1.5%, Fig. 2f, i, j). On the bog side, relief was more subtle with a range of ~0 to 0.8%. With the exception of one (D1; Fig. 2j), the transects with a lower mineral slope also presented a lower bog slope. Bogs with a higher slope also had a lower concavity index as determined by fitting a second order polynomial to LiDAR ground returns (note that negative values should be interpreted as higher convexity, and positive as concave). Average concavity of the bog for the 6 sites with a higher mineral slope was $-6.1 \times 10^{-05} \pm 7.0 \times 10^{-05}$, and $-2.0 \times 10^{-06} \pm 7.0 \times 10^{-05}$ for the remaining 4. The laggs bordered by an above average mineral slope (6/10) were found at the mesotopographic (local) minimum elevation. In contrast, for the 4 transects with a mineral slope below average, the lagg was not at the transect's minimum elevation. Based on the lateral slopes heading to the lagg, the 10 transects were placed into two geomorphic categories; 6/10 as “confined” transition, and 4/10 as “unconfined”, respecting terminology previously used by Hulmes (1980) and Morgan-Jones et al. (2005). Confined transitions had a topographic gradient sloping towards the lagg on both sides; a mineral slope ≥1.8%, and a bog slope ≥0.5%, and the elevation of the lagg centre was at the local minimum elevation. Bogs of confined transition tended to have higher convexity. Unconfined transitions had a lower, even negative mineral slope, and often a small vertical drop between the peatland's dome and the lagg. In unconfined transitions the lagg was not in a topographic depression, and usually not at the lowest point of the transition.

4.2. Vegetation height — the margin

Generally, vegetation height was lowest in the bog, to highest in the mineral terrain, but not always with a gradual, monotonic increase. Frequently, a ~10 m to ~100 m wide band of ~6 m high black spruce trees (*P. mariana*) occurred within the rand; in some instances adjacent to the lagg, at the bottom of the sloping margin (Fig. 3a), and others at the edge of the bog plateau, where the bog starts sloping (Fig. 3b). We refer to this band of black spruce as the rand-forest, and the outward sloping part of the bog as the rand-slope.

Along the lateral gradient, values for pH and EC_{corr} typically decrease from mineral land to lower rand (the first of the 3 ombrotrophic landscape units). Water extracted from mineral soils on average recorded pH of 5.2 ± 0.8; these values were lower in the lagg wells (4.8 ± 1.0), and then lower again, but changed little through the rand and bog sections (3.8 ± 0.4) (Fig. 4a). Electrical conductivities (EC_{corr}) in the mineral terrain (100 ± 56 μS cm^{-1}) and lagg wells (108 ± 83 μS cm^{-1}) were not statistically different; however they were significantly higher than both the rands (lower: 44 ± 35 μS cm^{-1}, higher: 30 ± 32 cm^{-1} μS) and bog units (27 ± 24 μS cm^{-1}) (Fig. 4b).

Seven of the 10 transects developed a rand-forest: 4/7 at the lower edge of the rand-slope, adjacent to the lagg (e.g. Fig. 3a), and 3/7 grew at the edge of the bog plateau (e.g. Fig. 3b), where the hydraulic and topographic gradients are steepening. In the rand-forest, *Sphagnum* mosses were absent or occurred only where the tree canopy was thinner. For the 3 transects without a rand-forest, the vegetation height gradually increased from the rand-slope towards the mineral forest (Fig. 3c). For 5/10 of the transects, the vegetation in the lagg was significantly lower ($p < 0.00$), compared to adjacent landscape units (fall scan). The analysis of the upper 25% of the LiDAR returns (for these 5 transects) revealed that the average vegetation's height changes from 8.8 ± 1.8 m in the mineral forest closest to the lagg, and 6.0 ± 2.1 m on the bog side (often rand-forests) to 2.3 ± 1.6 m in the lagg.

4.3. Spatial variation in hydrochemical gradients

The growing season of 2011 received 42% more precipitation than the 30-year normal (Canadian Climate Normals 1971–2000, Bathurst NB). Precipitation was rather well distributed throughout the season with May being the wettest month (157 mm or 25%) and August being the driest (91 mm or 15%). For each month, a rain event over 40 mm was recorded (Environment Canada Meteorological Tower at Bas-Caraquet, N.-B. (47°48′08 N, 64°50′00 W)).

4.3.1. Lateral gradient (from bog to mineral land)

To assess the similarities and differences between the geomorphological categories and landscape units, 4 variables were statistically tested, pH, EC_{corr}, water levels ($n = 90$), and hydraulic conductivity (K_{sat}) ($n = 40$). ANOVA showed no significant difference between the means of the 2 types of transitions (confined/unconfined, within similar landscape units) for EC_{corr}, pH and K_{sat}, but did for water table ($p = 0.003$), where water levels in the mineral land as well as in the lagg differ between the two transition types (Fig. 4a, d). Topography aside (i.e. when the data were pooled by landscape units regardless of their geomorphological characteristics) there was a significant difference between at least one of the means of the 5 landscape units

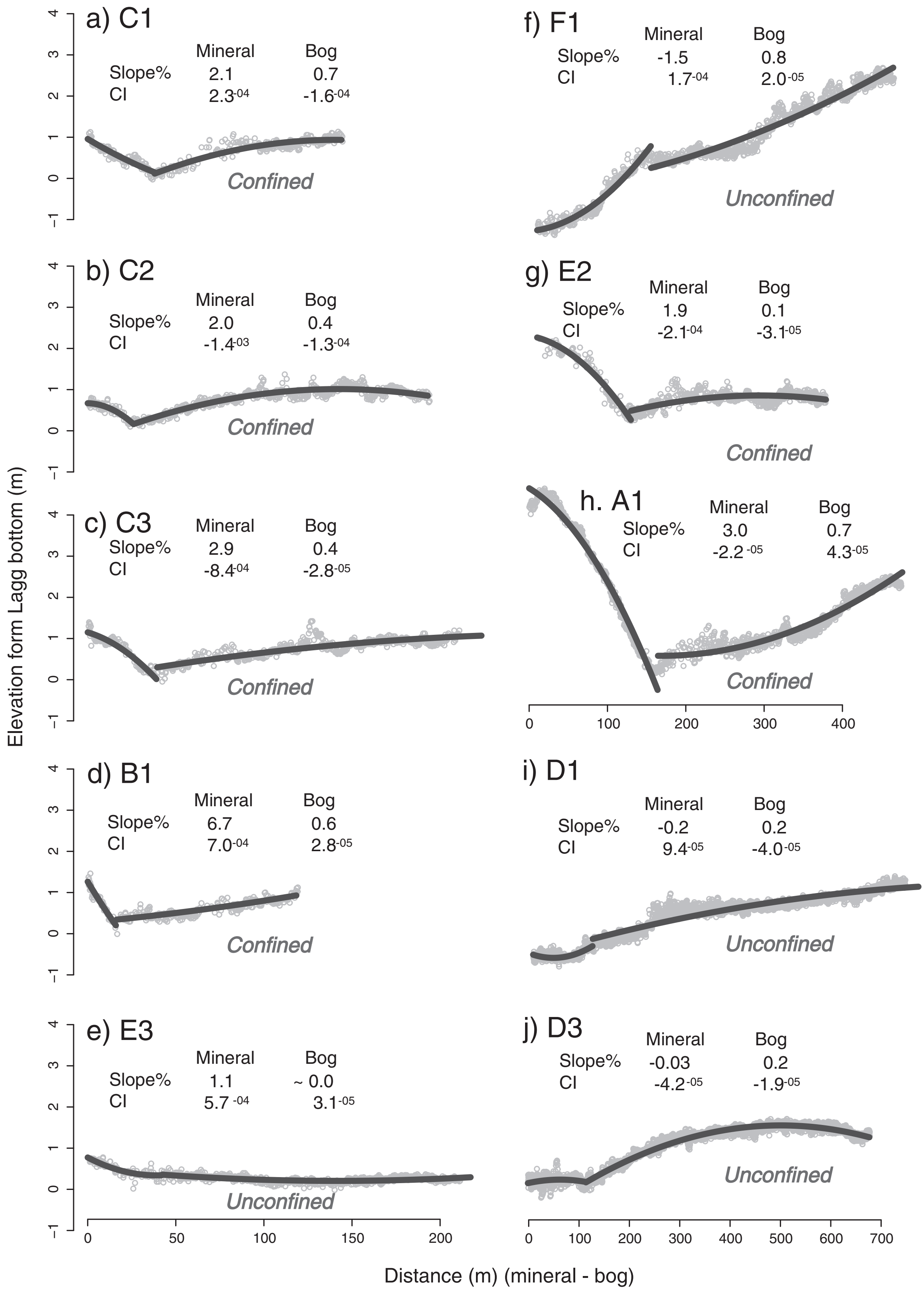


Fig. 2. Concavity index (CI) and lateral slope. The dark line is a quadratic fit of a 10 m buffer LiDAR ground return extraction (grey shadow) for each transect. The model was fitted between the local maximum elevations on each side of the lagg, with the exception of transects F1, D1, and D3 which had negative mineral slope. Based on slope, the transects were placed in two topographical categories: confined and unconfined. Transect locations are given in Table 1.

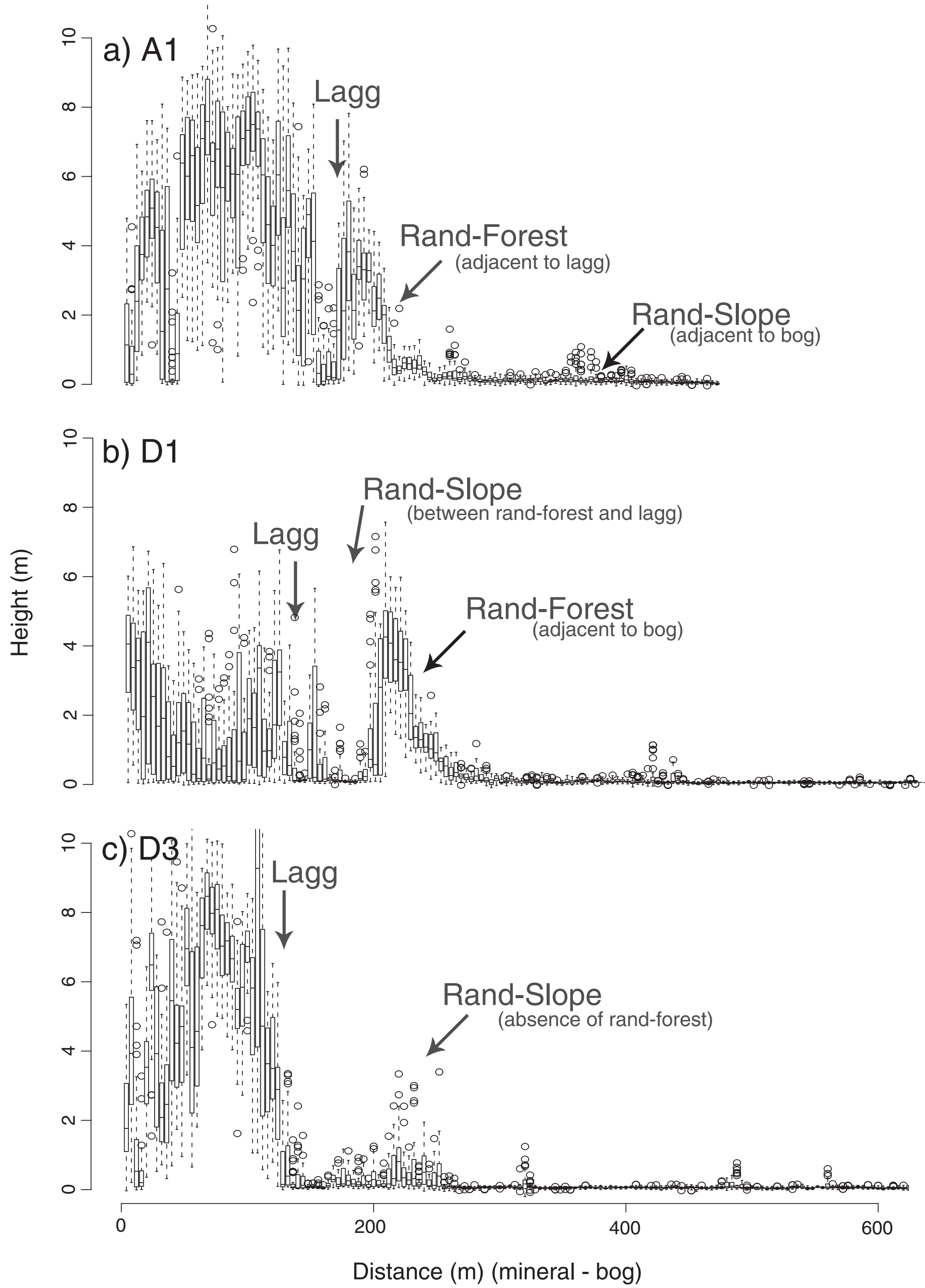


Fig. 3. (Left): Vegetation patterns from moving window. Examples (box and whisker plots) of the residual vegetation elevation (vegetation height) (DSM–DEM) where a) a rand-forest developed adjacent to the lagg. b) a rand-forest is found at the edge of the bog dome, and c) vegetation in the rand-slope increases towards the mineral land. Window size is 4 m, with a 2 m increment (n = 40/window). Caption for Fig. 4 explains how to interpret the boxplot.

($p < 0.00$). LSD (Fisher) tests were therefore performed to investigate the nature of this dissimilarity.

Fig. 5 illustrates the minimum and maximum water table positions for each site with respect to the ground surface as measured by the DGPS survey. Water levels were lowest in the mineral sites (-33.6 ± 20.1) and highest in the lagg, with an overall above ground average (6.9 ± 9.6 cm; Fig. 4d). Water table depths for the rands (lower: -10.2 ± 7.5, higher: 13.4 ± 9.9) and bog (-12.0 ± 7.5) were not significantly different from one another (Fig. 4d). Hydraulic gradients were usually highest in the rand leading to the lagg. For half of the transects (B1, C1, D1, D3, F1: Fig. 5), the mean hydraulic gradient was sloping towards the mineral land and away from the lagg. Specific discharge (q), calculated from lower rand to lagg and from mineral land to lagg suggests that on average, water tends to move away from the lagg and

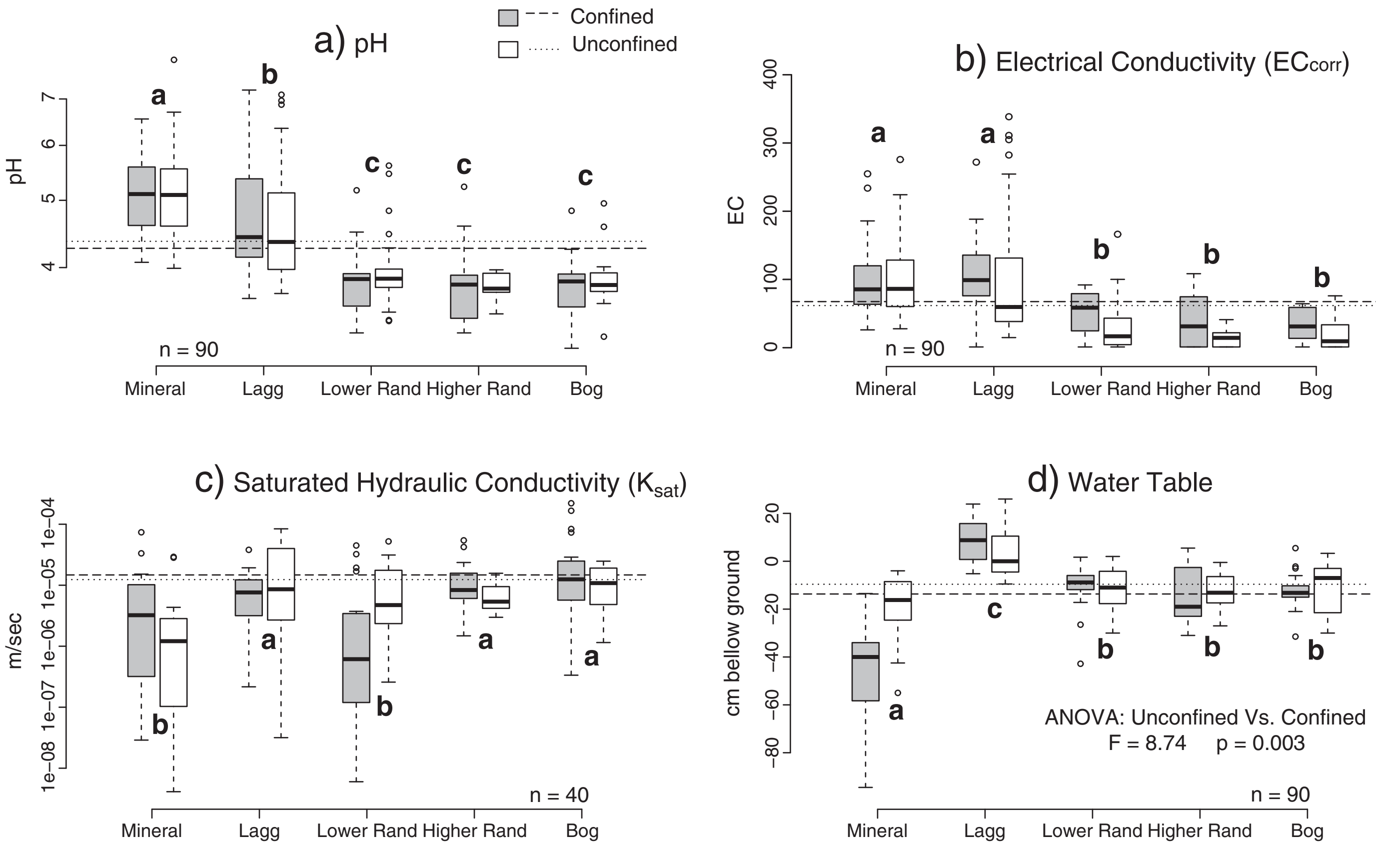


Fig. 4. (Bottom) Lateral hydro-chemical gradients. Box and whisker plots of the lateral hydro-chemical gradients. The horizontal line within the box indicates the median, boundaries of the box indicate the 1st and 3rd quartiles, the whiskers indicate maximum and minimum values within 1.5 interquartile range (IQR), and the individual points are values outside 1.5 IQR. ANOVA shows significant differences between at least one of the landscape units for all hydro-chemical variables ($p < 0.00$). Fisher Least Significant Difference (LSD) test, shows that with the exception of saturated hydraulic conductivity (K_{sat}), the bog units (bog, higher and lower rands) are not significantly different, but the lagg, bog and mineral land are. For the two transition types, ANOVA shows significant difference only for water table levels ($p = 0.003$), which differs (unconfined vs. confined) in both the mineral land and lagg. Dotted lines represent the mean per transition type. Groups with similar letters on the graphs are not significantly different as defined by the LSD test, for variables pooled by landscape units regardless of their geomorphological category.

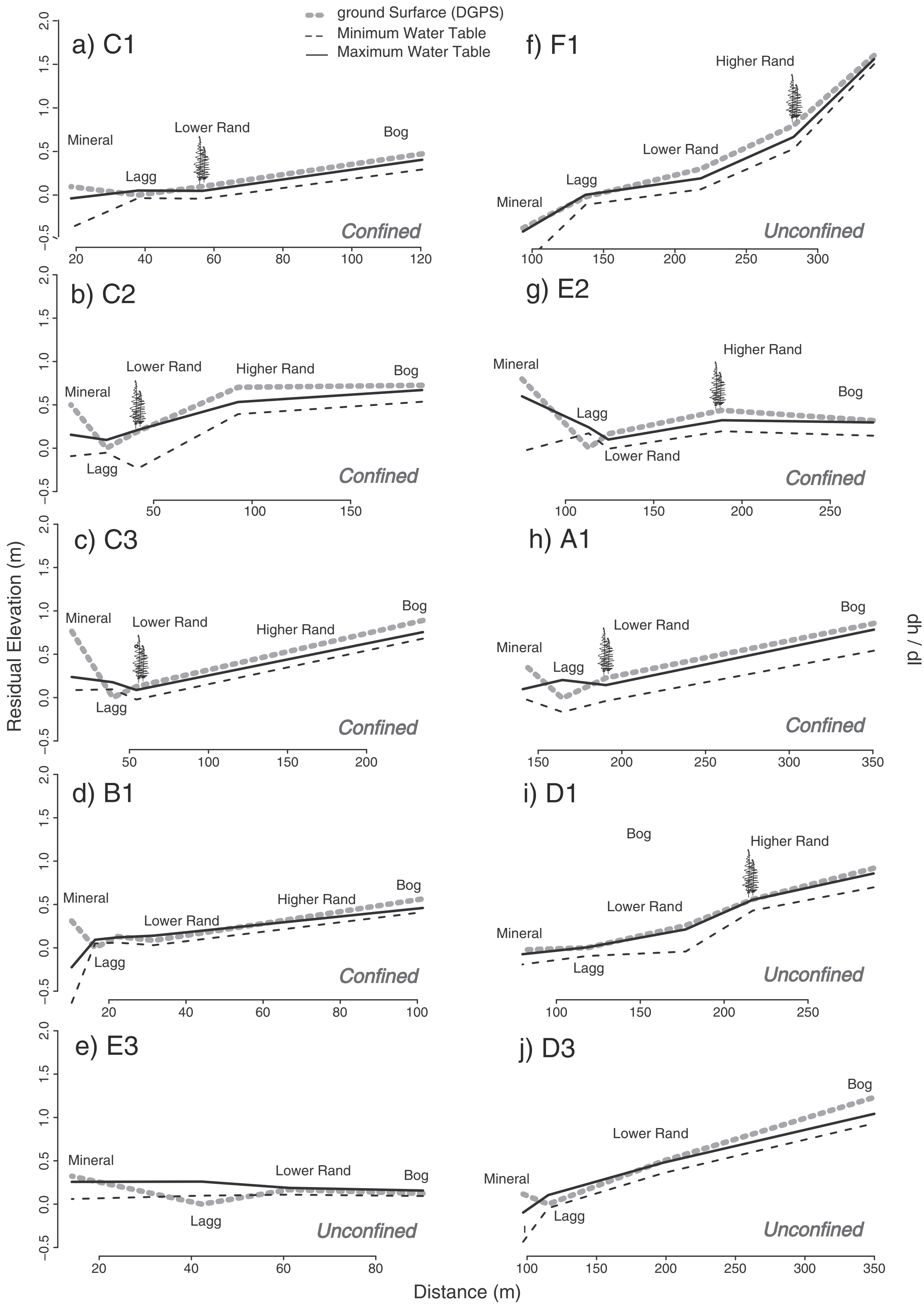
towards the mineral land at a highly variable rate (from 10 mm d^{-1} (F1) to 0.005 mm d^{-1} (E3)). For 3 out of the 10 transects, however (all confined), the mean mineral hydraulic gradient sloped towards the lagg, resulting in specific discharge (q) for these locations between 2 mm d^{-1} (C2) and 0.16 mm d^{-1} (C3, E2).

4.3.2. Vertical gradient in the lagg (from surface water to mineral soils)

For the lagg, pH and EC_{corr} increased with depth for both confined and unconfined transitions, from 42 ± 67 μS cm^{-1}, and 4.5 ± 1.3 pH at the surface to 210 ± 247 μS cm^{-1}, and 5.9 ± 1.2 pH for the deeper piezometer (Fig. 6). One transect (D3) consistently recorded higher than average values, up to 885 ± 397 μS cm^{-1}, and 8.0 ± 0.5 pH for the deeper piezometer. Saturated hydraulic conductivity (K_{sat}) was typically at its highest in the peat layer (~10 cm above the mineral interface) (Fig. 6c) — comparable to that of the bog (Fig. 4c), and at its lowest ~10 cm below the mineral interface (mid-depth piezometers). For pH, EC and K_{sat}, there was a significant difference between values from the mineral soil (Fig. 6), and those from the organic soil. Furthermore, ionic composition also increased with depth (Fig. 6d). Average concentrations of Ca ranged from 4.4 ± 4.8 mg/l in the surface waters to 14.7 ± 15.6 mg/l found in the deepest piezometers. Average concentrations of Mg were 1.1 ± 0.7 at the surface to 4.7 ± 3.7 in the deeper instruments (Fig. 6d). The respective values for K, Na and Cl were 1.9 ± 1.0 mg/l and 2.5 ± 0.9 mg/l, 5.5 ± 3.6 mg/l and 5.6 ± 1.8 mg/l, and 13.22 ± 11.2 mg/l and 13.5. ± 8.1 mg/l. Considering the small number of samples (n = 5/depth), and the high variability of the pore water collected in the mineral soils, we decided against statistical comparison between transition types, but are presenting descriptive statistics in Fig. 6d.

Seven out of 10 laggs showed evidence of upward fluxes within the peat layer (between the mid-depth piezometers and the wells) (Fig. 7). For the mineral soil (between the deeper and mid-depth piezometers), the fluxes were much smaller, yet 6/10 sites displayed upward water movements, confirming the lagg as a discharge zone, at least periodically. As for the peat–mineral interface (between the mid-depth and shallow piezometers), the fluxes were even smaller, and half the instruments recorded negligible flow. Nevertheless, 3 of the lagg studied showed small upward water movements through the interface. The 2 strongest upward fluxes recorded in organic soils (shallow-well) were observed in unconfined transitions (D3 & E3, Fig. 7). In contrast, the few downward fluxes observed within the peat layer (well-shallow) were observed in two transects with strong mineral slopes (1.9% (C3)–2.9% (E2) — confined transitions), and a relatively small lateral slope (0.1% (E2)–0.4% (C3)) on the peatland side (Figs. 2 & 6).

Fig. 5. Lateral hydraulic gradients. Ground surface (from DGPS survey) and minimum and maximum water table for each transect. The hydraulic gradient of confined transition generally slopes towards the lagg. At minimum water table, however, it has the tendency to slope away from it. Thus, mean hydraulic gradient does not always follow topography. Sketched trees indicate the location of a rand-forest.


ground Surfarce (DGPS)
Minimum Water Table
Maximum Water Table
Residual Elevation (m)
Distance (m)
dh / dl
a) C1
Mineral
Lagg
Lower Rand
Bog
Confined
b) C2
Mineral
Lagg
Lower Rand
Higher Rand
Bog
Confined
c) C3
Mineral
Lagg
Lower Rand
Higher Rand
Bog
Confined
d) B1
Mineral
Lagg
Lower Rand
Higher Rand
Bog
Confined
e) E3
Mineral
Lagg
Lower Rand
Bog
Unconfined
f) F1
Mineral
Lagg
Lower Rand
Higher Rand
Unconfined
g) E2
Mineral
Lagg
Lower Rand
Higher Rand
Bog
Confined
h) A1
Mineral
Lagg
Lower Rand
Bog
Confined
i) D1
Mineral
Lagg
Lower Rand
Higher Rand
Bog
Unconfined
j) D3
Mineral
Lagg
Lower Rand
Bog
Unconfined

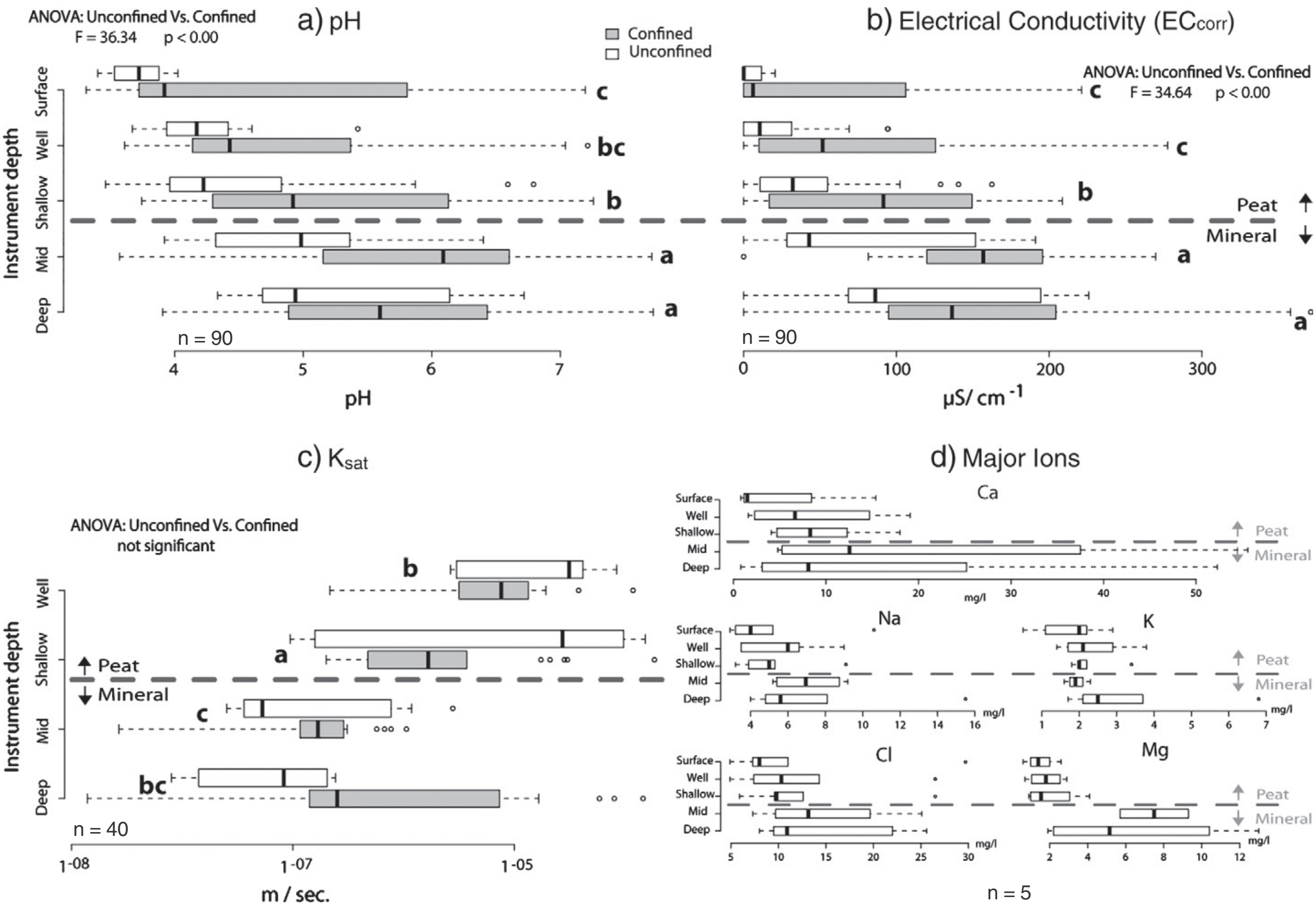


Fig. 6. Vertical gradients (lagg). For pH, EC_{corr}, and K_{sat}, ANOVA shows significant differences between at least one of the measurement depth ($p < 0.00$). Fisher Least Significant Difference (LSD) test, shows that for pH, EC, and K_{sat}, there is a significant difference between the surface, organic, and mineral waters. For the two transition types, ANOVA shows significant difference for both pH and EC ($p < 0.00$), confined transition having higher values. Lower pH and EC_{corr} values for the surface waters of the unconfined transitions suggest a stronger influence of the bog water inputs. Groups with similar letters on the graphs are not significantly different. Dotted line indicates the interface between organic (above) and mineral (below) soils. Absolute piezometer depth differed for each site (see Section 4). Values in this figure exclude transect D3. Caption for Fig. 4 explains how to interpret the boxplot.

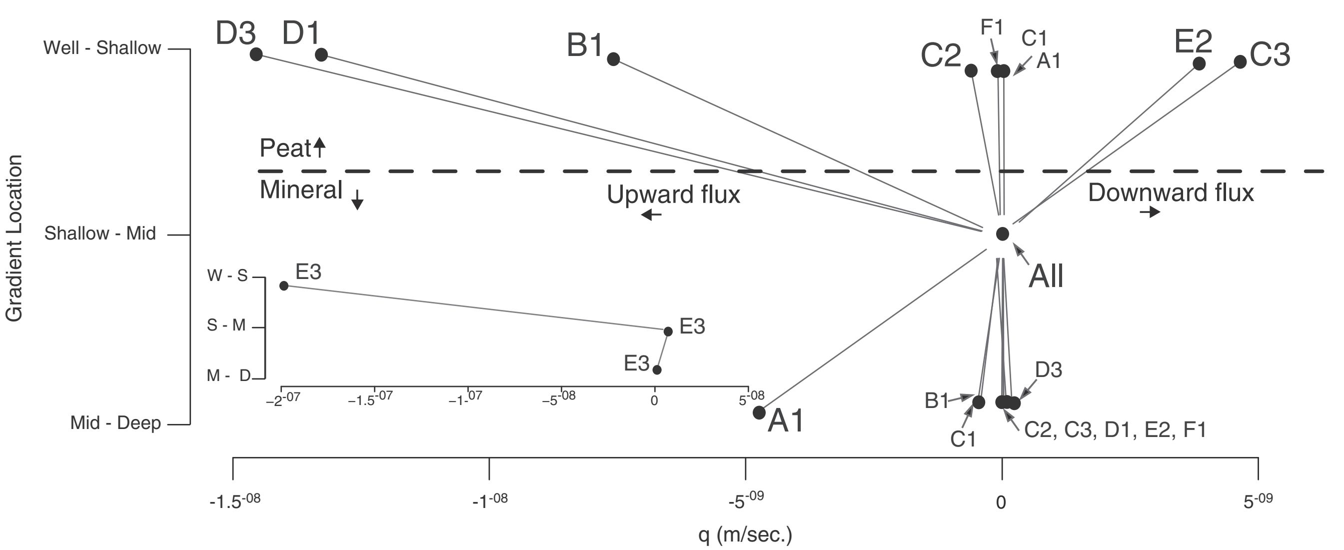


Fig. 7. Vertical fluxes within the lagg ($n = 10$). Values were calculated from higher to lower screen (suspected origin of flow-destination), starting with the well to the shallow piezometer, the shallow to the mid-depth piezometer, and form the mid-depth to the deep piezometer. Unconfined transitions (D1, D3, E3, and F1) show a tendency towards upward fluxes from the organic peat layer (well-shallow), especially for E3, which is one order of magnitude faster (inset graph). Some confined transitions, however, tend to downward fluxes in the top peat layer (well-shallow), and upward fluxes within the mineral soil (mid-deep). In all cases, negligible fluxes were recorded at the peat mineral interface (shallow-mid). A negative gradient indicates upward flux.

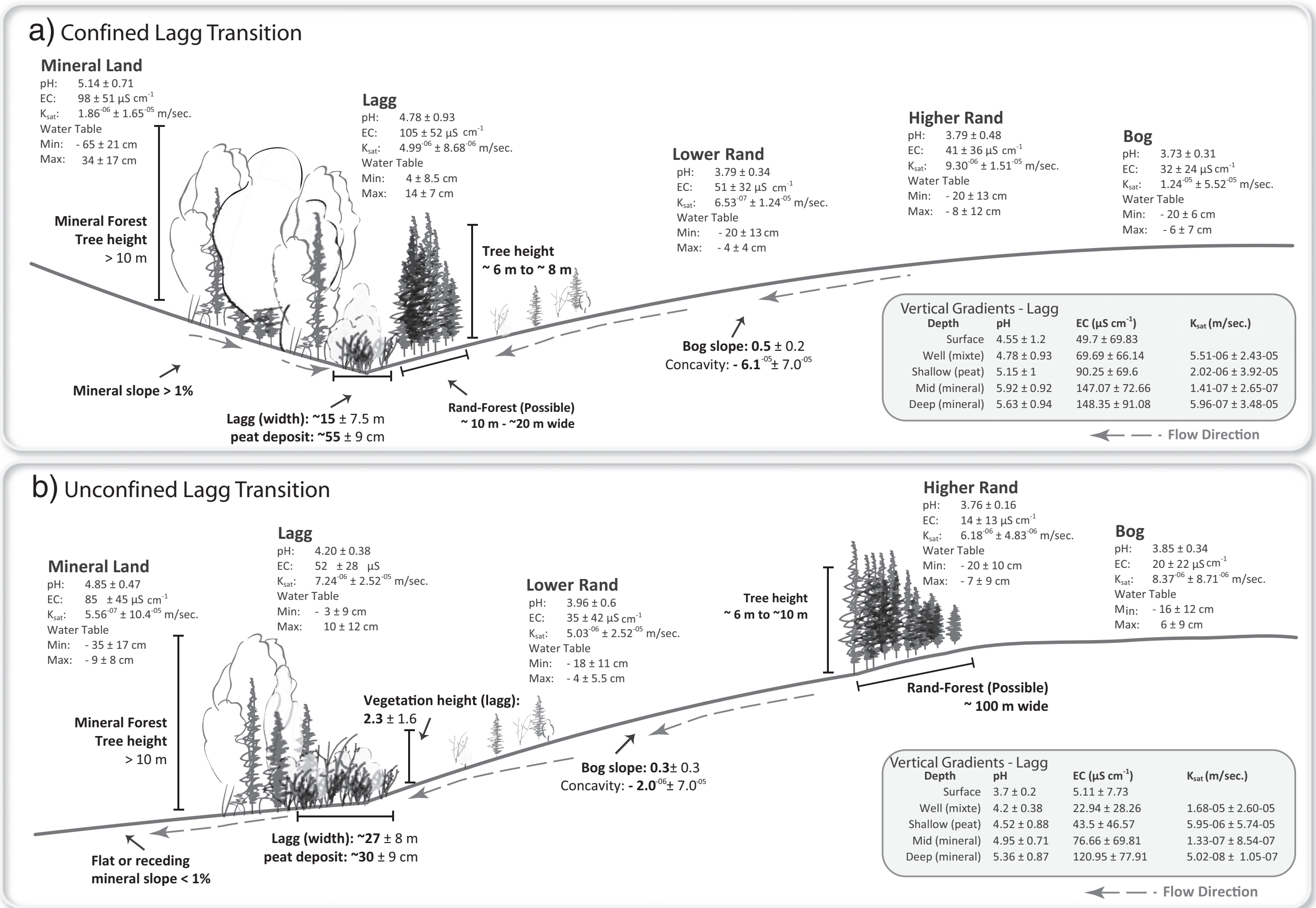


Fig. 8. Conceptual model — Atlantic provinces. Landscape units (lateral) and lagg depth with associated hydro-chemical and morphological characteristics for confined (n = 6) and unconfined (n = 4). Chemical values reported for the unconfined transition exclude transect D3 which recorded unusually high values, unfit for generalization.

5. Discussion

5.1. Major controls: topography and hydrology

We identified two main topographic settings (confined and unconfined; Fig. 8) and three vegetation patterns (rand-forest adjacent to the lagg, rand-forest at the edge of the bog dome, absence of rand-forest; Fig. 3) for the transition between bog and mineral forest. Such morphological differences have been previously mentioned by Whitfield et al. (2006), Howie et al. (2009, 2013) and Morgan-Jones et al. (2005), but without distinguishing their respective hydrochemical and hydrological properties. Although the confined vs. unconfined morphology had little influence over the general chemistry of the transition, it did impact the amount, fluctuation, and ratio of bog/mineral water input to the lagg zone. In confined transition (Fig. 8a) the bog met a relatively sharp mineral slope (the upland) and the lagg was found at the local minimum elevation of the transition. Because it was spatially confined between the bog and the mineral terrain, this type of lagg tended to be narrow (~15 ± 8 m), with a substantial peat layer (~55 ± 9 cm), and consistently high water levels (9.0 ± 8.3 cm). This type of lagg was easiest to identify as both its vegetation and water levels changed distinctly on each side. In times of high precipitation or at snow melt, water levels in the lagg rose above the local micro-topography – which normally locally traps the water in stagnant puddles – and flowed laterally (parallel to the peatland), creating a lagg stream that removed excess water from the system (cf. Godwin and Conway, 1939). For unconfined transitions (Fig. 8b), the bog met a flat or receding slope (sloping away from the lagg), and was not at the local minimum elevation. Because it was not spatially limited in the way confined transitions were, these laggs tended to spread more widely across the landscape (~27 ± 8 m), and were difficult to clearly identify on the basis of vegetation patterns. Water levels were lower (3.7 ± 10.7 cm), falling at or below ground level in late summer, and the peat layer was thinner (~30 ± 9 cm). Recognizing the lateral extent was most challenging for this type of lagg.

Chemically, we found no significant differences between the 3 landscape units of the bog (bog, higher rand, and lower rand), or between the two types of transition (confined and unconfined, when all landscape units were pooled together). Chemical differences occurred between the mineral land, the lagg, and the bog units, regardless of their geomorphic shape. However, when the remarkably high pH and EC values in the lagg of transect D3 were removed from the analysis, the laggs from confined transitions became significantly ($p < 0.00$) richer in both pH (4.8 ± 0.9 vs. 4.2 ± 0.4) and EC_{corr} (105 ± 52 µS cm^{-1}, vs. 52 ± 28 µS cm^{-1}) (well instruments; Figs. 6 & 8). Surface water values in the lagg, especially for unconfined transition, were observed to be comparable to concentration found in the bog units (Fig. 6), suggesting a stronger influence/proportion of bog water (runoff) than for confined transition. Paradis et al. (2014) measured pH values in the peat of laggs for the same region in New Brunswick to be 4.4, and found no significant differences between the lagg and the bog in terms of EC_{corr}, and cation concentrations. These low values compare to the ones we have recorded in the pore water of the peat found in unconfined laggs (4.5 ± 0.8), and in the standing water of the confined lagg (4.6 ± 1.2). However, as mentioned above, pore water chemistry rapidly changes with depth in the lagg, and is influenced by nearby topography. In addition to different water chemistry in the lagg, hydrology and vegetation patterns also distinguish the two geomorphological categories, with the confined transition having the tendency to grow a rand-forest adjacent to the lagg. In contrast, the vegetation heights increased more gradually towards the lagg when the rand-forests were observed closer to the dome (unconfined transitions), or when no rand-forests were observed.

In a raised bog, water moves mostly through the acrotelm from the dome towards the edge of the peatland (Clymo, 1984). Based on two-dimensional groundwater flow and flow sensitivity models, Lapen et al. (2005) suggested that saturated hydraulic conductivity (K_{sat}) must be higher at the centre of the peatland, but significantly reduced at the margins. This was later confirmed by Baird et al. (2008), and more recently by Lewis et al. (2012). Our results are in accordance with these studies, as K_{sat} recorded at the lower rand location was significantly lower than at the bog and higher rand (Fig. 4c). Although we did not measure bulk density, Lewis et al. (2012) reported similar results to correspond with sections of the margin where shallower peat of higher bulk density and shear strength was found. This might be especially pertinent for confined transition, where the lower rand was vegetated by a thick band of black spruce with little to no *Sphagnum*. This shift in vegetation affects the composition of the top layer of peat, which presented hemic properties (moderately to well decomposed), and lower K_{sat} (Fig. 4c). When the water draining from the bog and higher rand reaches the lower rand, the reduced K_{sat} at this location helps retain water within the peat resulting in a higher water table (although not significant), slowing the outward movement of bog water to the lagg. As suggested by Price (2003), this could be an important self-preservation mechanism for bogs. However, we observed lower water levels in the rand-slope when a rand-forest grew in the higher rand rather than adjacent to the lagg. Rand-forests occurring at the higher rand, which reduces K_{sat}, could favour the retention of water in the more central part of the bog (dome). Baird et al. (2008) suggest this low peripheral K_{sat} to be important to bog development.

In the lagg, we consistently observed a layer of densely compacted soil directly below the peat layer, which had K_{sat} (mid-depth piezometer) significantly lower than that of the overlying peat layer (Fig. 6c). Consequently, in confined transition, water moving down the bog through the acrotelm and down the mineral land slope becomes trapped laterally between two landscape units of lower K_{sat}, and vertically constrained by a low permeability layer below the peat. For unconfined transition, we often observed upward water movement from the shallow piezometers (Fig. 7), which could help explain some of those laggs being consistently wet despite the low topography.

In some cases, the hydraulic gradient on the mineral side of the lagg did not always follow the topography, resulting in some of the confined transitions (B1 and C1) to have a flat or even negative water table gradient (away from the lagg), especially at minimum water table (Fig. 5). In general, most of the groundwater inflow to the lagg came from the bog. Only 3/10 transects were on average receiving water from both the bog and the mineral land (E2, C2, C3; Fig. 5). For two of these transects (E2 and C3) the lateral contribution of mineral water input was small (specific discharge: 0.18 mm d^{-1} and 0.16 mm d^{-1}, respectively); specific discharge from mineral slopes was about 1% of that measured from bogs. However, at transect C2 (located only 150 m from transect C3) the situation is reversed; the specific discharge from the bog (0.18 mm d^{-1}) was only 1% of that from the mineral side (2 mm d^{-1}). Comparing the two locations, transect C2's mineral soils were composed of coarse sand to a depth of ~55 cm, and K_{sat} was high ($8.9 \times 10^{-06} \pm 5.2 \times 10^{-06}$ m s^{-1}) whereas C3 was lower ($1.5 \times 10^{-06} \pm 3.3 \times 10^{-07}$ m s^{-1}). Furthermore, at C2 the low K_{sat} of the peat below the lower rand-forest ($6.3 \times 10^{-08} \pm 2.6 \times 10^{-07}$ m s^{-1}) reduced the flow of bog water to the lagg. The close proximity of these two transects (C2 and C3) and their contrasting flow dynamics illustrate the potential variability of lagg function within a given peatland. Overall, however, groundwater flows during the measurement period were all relatively low and probably make only a small contribution to the lagg water budget (which we did not measure), albeit a larger contribution to the water chemistry. Flows during the snowmelt period are likely much more important, and strongly influence water levels over the ensuing summer period.

Water levels in the lagg were consistently high. This was especially true for confined transitions, where minimum water table ($n = 6$) was 3.7 ± 8.4 cm generally reached in October, and maximum water table was 13.3 ± 6.0 cm (Fig. 4). For unconfined transitions ($n = 4$), minimum water table was -3.3 ± 9.0 cm and maximum was 9.9 ± 11.6 cm. Unconfined laggs, where water was "lost" to the mineral side, had a somewhat more variable water table, and were more diverse in their character; some dryer and others wetter and richer despite the low mineral topography. Given the prevalence of ponded water in the laggs, the water table variability was not as great as for an equivalent water storage change in a soil matrix (i.e. where the specific yield is $\ll 1$); this increased the overall variability in water table in unconfined laggs (since they were less likely to have ponded water).

5.2. Landscape units and vegetation height

The motivation behind the documentation of the changes and variation in vegetation height throughout the transition comes from the difficulty to identify and map the location of the lagg around a bog. Howie et al. (2009) theorised that lagg location (prior to disturbance) for Burns Bog could be, based on vegetation height, extracted from historical stereographic photos, but suggested that LiDAR technology might be best for this purpose. If there is a pattern for the recognition of lagg location, it could be extracted and mapped from both traditional and computerized stereography, as well as LiDAR data.

Vegetation height (based on LiDAR analysis) generally increased from the bog plateau through the transition zone to the mineral terrain; we documented three distinct patterns (Fig. 3). At 4/10 locations, we observed a band of black spruce 10–25 m wide, along the edge of the peatland, adjacent to the lagg (e.g. Fig. 3a). These were at the very foot of the rand-slope, and associated with confined transitions and wetter laggs. We observed more prevalent and deeper ponding of water in these laggs (6.6 ± 7.5 cm; e.g. Fig. 5a, b, c, and h) than for sites with a rand-forest closer to the bog plateau (-3.0 ± 3.2 cm; e.g. Fig. 5f, g, and i). Downslope of these lower rand-forests, the lagg typically supported more minerotrophic vegetation better adapted to regular flooding (e.g. *A. incana* ssp. *rugosa*, *Ilex mucronata*, *V. nudum* ssp. *cassinoides*), or constantly wet conditions (e.g. *Myrica gale*, *Calamagrostis canadense*, *Carex aquatilis*). In these cases, there was a clear drop in the vegetation height in the lagg, which makes the boundary between peatland and lagg more distinct and easier to extricate (A1, C1, C2, C3, and D1). The rand-forest that was adjacent to the plateau grew on the steeper part of the rand (slope > 0.6%), between ~150 and 200 m from the lagg; trees were generally ~6 m but up to ~10 m high, and occupied a band >100 m wide (e.g. Fig. 3b). We associate the rand-forest found in the higher rand with unconfined transition and poorer/dryer lagg. As previously suggested, the lower K_{sat} associated with the peat of the rand-forest retains more water in the dome. Water levels for rand-slope following an upper rand-forest were generally lower than for rand-slopes lacking a rand-forest, or where it was located adjacent to the lagg (Fig. 5). Damman and Dowhan (1981) also documented a slope forest found in the steepest and best drained part of Western Head bog slope (Nova Scotia). The data suggest that the low K_{sat} associated with rand-forests is important in retaining water in the domed bog.

6. Conclusion

The laggs studied shared key characteristics; high water levels, water chemistry influenced by both the bog and mineral terrain, and a low-permeability mineral soil layer below a shallow peat deposit. The most important distinction between the laggs related to whether or not they were "confined" by a mineral slope directing flow towards the lagg, or away from it (unconfined). These two geomorphological models are shown in Fig. 8. The topographic factor was a major control for the formation and function of the lagg, dictating water flow rates and direction, which in turn affects water chemistry and most likely nutrient transport and availability, hence vegetation characteristics (see Paradis et al., 2014). Confined laggs were generally wetter and supported higher pH and EC values than unconfined. Outside of the laggs themselves however, there were no significant differences between the chemistry (pH and EC) of the two geomorphological categories. If water table position for unconfined transition was higher in the mineral terrain and lower in the lagg than for similar landscape units of the confined transitions, it was however comparable for all bog units (lower rand, higher rand, and bog), and all transects studied. In this sense, our data suggests that spatial variation within a single peatland may be more significant than between them. Moreover, it must be noted that although some of our sites were not as obviously hosting a lagg (F1) as others (A1), we selected each one based on known lagg characteristics (relatively high water level, transitional vegetation and chemistry), but that laggs were not present (or recognized) at all location along the margin of any given bog. Systematic instrumentation of a single peatland to document the range of margin conditions and functions could help to further understand the connectivity between bog and mineral land, and the role of laggs as a water conveyance feature.

We agree with Howie et al. (2009) that the changing height of the vegetation approaching the edge of a peatland could be used to predict the presence and perhaps some key characteristics of a lagg. In mineral terrain noticeably sloping towards the peatland, laggs of confined transitions were often (4/6) bordered by a lower rand-forest on the bog side (e.g. A1, C1, C1, C3), which we associate with deeper and more consistent ponding of water. Thus, following the rand-forest (located in the lower-rand), vegetation height is lowered in the lagg, to then rise again in the mineral terrain in a way that could be depicted from LiDAR's vegetation residual elevation returns. In some cases, however (e.g. D3, Fig. 3c), this shift in vegetation is much more subtle. It is therefore unclear if the vegetation gradient (height) alone is sufficient for the delineation of lagg boundaries. We are currently working on identifying the necessary information and exploring techniques that could detect the edge of the lagg from LiDAR data (Langlois, 2014).

Up to now, the margins of bog peatlands have not been recognized as an integral and essential part of a peatland ecosystem. This research has demonstrated that the features of the transition zone that include the lagg, influence the quantity and variability of water within the peatland, and should be considered as integral part of the peatland complex. The rand-forest was associated with a lower hydraulic conductivity in the peat that plays a role in regulating water outflow from the bog. Until now, the poor understanding of lagg function (actually, of the entire transition zone), has made it difficult for resource managers to defend these relatively small, inconsistent, and often difficult to identify systems, and thus protect them from development. Furthermore, the role of the bog margin, including the lagg, should not be overlooked in peatland restoration projects. Where the lagg of a disturbed peatland has been drained or otherwise compromised, restoration measures should recognize the functions the lagg may have originally performed in sustaining high water tables within the bog, and as a conduit for flow during wet periods. Establishing the hydrological role of this ecotone on the integrity of the peatland as a whole is therefore essential not only for the improvement/development of restoration techniques inclusive of bog's margins, but also for resource managers to be able to make informed decision about the impact of projects located within the margin, or in the peripheral areas of bog peatlands.

Acknowledgments

We would like to thank Etienne Paradis (Laval University) for his help choosing the study sites, and for his comments on the manuscript. Thanks to the New Brunswick Department of Natural Resources for providing the LiDAR data and helping with the DGPS survey. This study was funded through Dr. Rochefort's NSERC Industrial research (PCIPJ 282989-07) chair in peatland management as well as a NSERC Discovery Grant: RGPIN 174626-2008 (Price).

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