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Predicting export of dissolved organic carbon from forested catchments in glaciated landscapes with shallow soils

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[1] This study presents a simple model of dissolved organic carbon (DOC) loading to surface waters that is applicable to headwater catchments in forested regions on glaciated landscapes. Average annual DOC export was highly variable among the 33 experimental catchments along an east-west transect, ranging from 0.90 to 13.74 g C/m^2/a. It was hypothesized that the proportion of wetlands within the catchments would explain the majority of variation in average annual DOC export. To test this hypothesis, digital terrain analysis was used to derive wetlands automatically under both open and closed forest canopies by identifying the probability of a grid cell being a depression and/or flat. Using a 10 m digital elevation model (DEM) derived from readily available sources, the proportion of wetlands explained 63% of the variance in average annual DOC export among the 33 experimental catchments. Inclusion of regional climatic indicators, including the number of growing degree days (with a base of 10°C) and the runoff coefficient, increased explanation of variance from 63% to 89%, once catchments with lakes (>5% of catchment area) adjacent to the catchment outlets were removed. This study shows that DOC export can be predicted accurately from headwater catchments in forested regions on glaciated landscapes using a simple model based on the proportion of wetlands and easily calculated climatic variables.

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1. Introduction

[2] Dissolved organic matter (DOM) represents only a minor component of the global carbon cycle [*Neff and Asner*, 2001]. DOM is operationally defined as the organic carbon that passes through a 0.45 μm filter [*Moore et al.*, 1998] and contains organic compounds ranging from low molecular weight, simple amino acids and sugars to higher molecular weight, complex fulvic and humic acids [*McKnight et al.*, 1985]. DOM provides an important energy and nutrient (e.g., carbon, nitrogen, sulfur and phosphorus) source for aquatic primary productivity [*Hobbie and Wetzel*, 1992; *Hedin et al.*, 1995; *Vitousek et al.*, 1998; *Neff and Asner*, 2001]. DOM adsorbs trace metals and contaminants and when exported to surface waters, influences the exposure of aquatic organisms to these substances [*Thurman*, 1985; *Driscoll et al.*, 1993]. Changes in DOM export may affect the acid-base balance of aquatic systems [*Eshleman and Hemond*, 1985] and alter light penetration, including UV-B [*Schindler and Curtis*, 1997], which may be harmful to aquatic organisms [*Skully and Lean*, 1994]. Consequently, while DOM may represent only a minor component of the global carbon cycle, it is an important determinant of the structure and function of aquatic systems [*Neff and Asner*, 2001].

[3] In forests, dissolved organic carbon (DOC) loading to surface waters is influenced by topographic regulation of hydrologic flow paths within the contributing landscape [*McGlynn and McDonnell*, 2003; *Inamdar and Mitchell*, 2006; *Ogawa et al.*, 2006]. Within a catchment, upland soils may be a source of DOC; however, most of the DOC produced from freshly fallen litter and the forest floor is adsorbed on mineral soils and then mineralized back to carbon dioxide so that it never leaves the soil profile as DOC [*Webster et al.*, 2008]. Lowland (wetland) soils may also be a source of DOC. Previous studies have presented statistical models that use catchment characteristics to predict DOC loading to surface waters at local to regional scales [e.g., *Dillon and Molot*, 1997; *Aitkenhead et al.*, 1999; *Creed et al.*, 2003; *Xenopoulos et al.*, 2003] to continental and global scales [e.g., *Sobek et al.*, 2007]. The proportion of wetlands within catchments is perhaps the single most important determinant of DOC export at local to regional scales, whereas climate factors become

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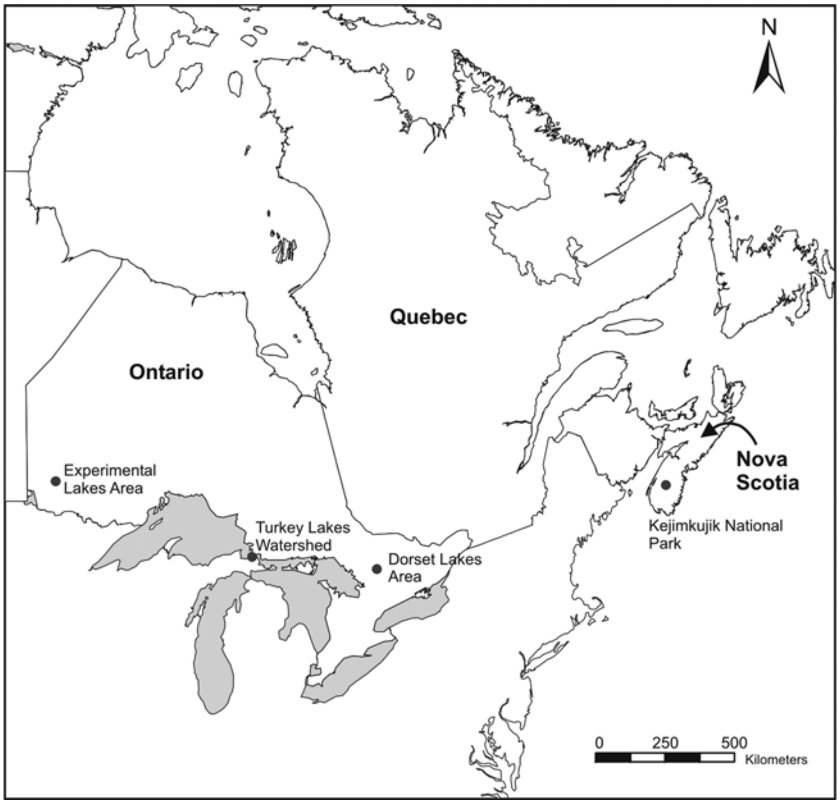

Figure 1. Location of study sites.

more important across regions and at continental to global scales. Given the extent to which DOC loading influences the structure and function of aquatic ecosystems, a useful tool would be a simple but robust model to predict DOC loading to surface waters across forested regions.

[4] Forested wetlands can be defined as areas where the water table is at, near, or above the ground surface long enough to enable the accumulation of organic matter with hydrologic pathways that bypass DOC sorption in mineral soils [*Tarnocai*, 1980]. These wetlands represent rich carbon stores as carbon accumulates in wetlands because of low

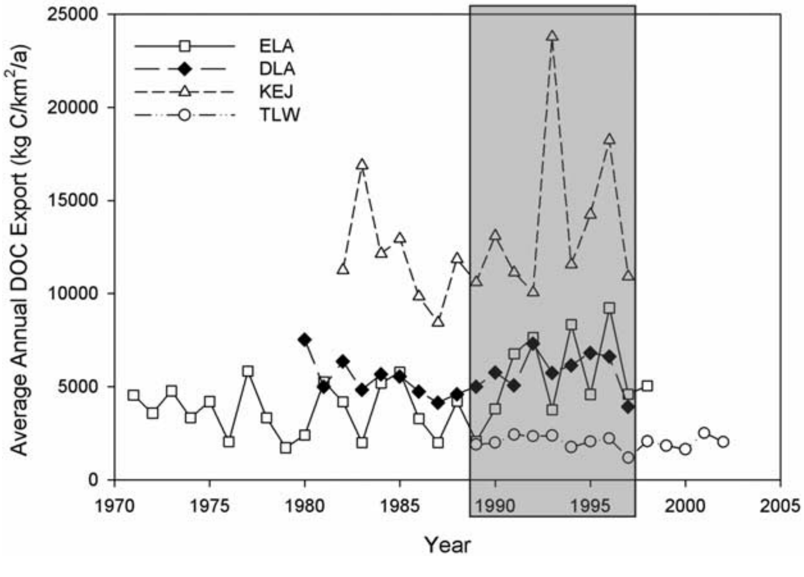

Figure 2. Temporal variability in regional average annual dissolved organic carbon (DOC) export for all data available in all regions. The time period used in this study is highlighted (1989–1997).

Table 1. Study Site Characteristics Including Ecozone or Ecoregion, Climatic Normals, Topographic Relief, Bedrock, Soils, and Forest Cover[a]

Location	Ecozone/Ecoregion	Mean Temperature (°C) Annual/January/July (Climate Station)	Total Precipitation (mm/a)	Relief (m)	Bedrock	Soils	Forest Type
ELA	Boreal Shield/Lake of the Woods Ecoregion	2.6/−17.0/19.2 (Rawson Lake)	689	70	Granite with frequent rock outcrops and thin till deposits.	Humo-Ferric Podzols in uplands and Humic Gleysols in lowlands	Major: jack pine, black spruce, trembling aspen, and white birch. Minor: white spruce, balsam poplar, black ash, red and white pine.
TLW	Boreal Shield/Lake Timiskaming Lowland Ecoregion	4.9/−10.1/18.3 (Sault Ste Marie 2)	1011	272	Precambrian metamorphosed basalt with small outcrops of basalt covered by thin till deposits.	Ferro-Humic and Humo-Ferric Podzols with dispersed organic soils found in depressions and adjacent to streams and lakes	Major: sugar maple. Minor: yellow birch, red maple, ironwood, and white spruce.
DLA	Boreal Shield/Algonquin-Lake Nipissing Ecoregion	4.8/−11.1/18.7 (Dorset MOE)	1068	96	Precambrian metamorphic silicate covered with thin till deposits.	Brunisols and Podzols form on well drained slopes while organic soils are common in areas where saturation occurs	Major: Sugar maple and trembling aspen Minor: white and black spruce, tamarack, eastern hemlock, yellow and white birch, red and white oak, basswood, and eastern white cedar.
KEJ	Atlantic-Maritime/Southwest Nova Scotia Uplands Ecoregion	6.3/−6.1/18.4 (Kejimkujik Park)	1399	100	Granite and/or slate with thin till deposits.	Humo-Ferric Podzols dominate the region; with Ortstein Podzols on deep sandy tills, Humic Gleysols or Fibrisols on raised and flat bogs, and Humic Mesisols on fens.	Major: white spruce Minor: red and black spruce, eastern hemlock, white and red pine, white birch, red maple, balsam fir, and red oak.

[a] ELA, Experimental Lakes Area. TLW, Turkey Lakes Watershed. DLA, Dorset Lakes Area. KEJ, Kejimkujik National Park.

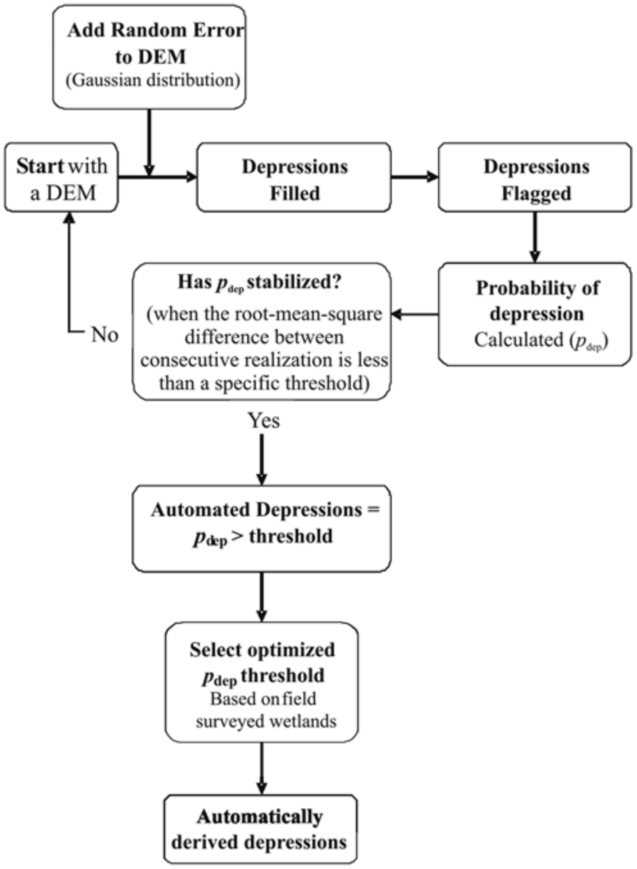

Figure 3. Flow chart depicting the stochastic modeling approach for automated wetland mapping.

rates of decomposition of organic matter [*Moore et al.*, 2007]. Carbon stored near the surface may be transformed to dissolved forms via both aerobic and anaerobic decomposition [*Kalbitz et al.*, 2000]. Under aerobic conditions, DOC may be formed during dry periods when decomposition occurs and the microbial products of this decomposition are subsequently flushed with the rising water table. Alternatively, under anaerobic conditions, DOC may be formed during anaerobic decomposition when the water table is at or near the surface and water-soluble metabolites are mobilized when water flows through the system. *Schiff et al.* [1997] used carbon isotopes to show that a significant fraction (>50%) of DOC in streams is composed of carbon that was recently fixed into organic matter, which is then decomposed and transported along hydrologic pathways.

[5] Most studies that examine the relationship between forested wetlands and DOC export define wetlands as features with an open or floristically distinctive canopy that can be easily detected by aerial photography or satellite imagery (i.e., bogs, fens, and/or marshes). However, forested wetlands are not as easily identifiable through this method. *Creed et al.* [2003] explored the role of wetlands concealed under a uniform canopy in DOC export. They observed that forested catchments with no apparent wetlands varied significantly in annual average DOC export. They mapped wetlands concealed underneath a forest canopy and found that these wetlands explained a majority (88%) of the variation in DOC export. The implication of this study is that DOC export models that fail to include concealed wetlands underestimate DOC export from those catchments.

[6] In this paper, a simple but robust model for predicting DOC loading to surface waters from forested catchments on glaciated landscapes is presented. An automated method was developed for detecting both open canopy and concealed wetlands from digital elevation models (DEMs) that are generally available from government agencies. This method was then used to explore the generality of percent wetland–DOC relations for experimental catchments established in the 1980s as part of the acid rain research program in eastern Canada. We tested whether or not a simple model can be developed to predict DOC loading to surface waters across the geographic range of experimental catchments.

2. Study Area

[7] The study included experimental catchments that were established to investigate the hydrology and biogeochemistry of forested landscapes in eastern Canada (Figure 1). A total of 33 headwater catchments were selected for this study. These headwater catchments included: 3 (NW, NE, and E inflows to Lake 239) in the Experimental Lakes Area (ELA) near Kenora in western Ontario; 13 (C31, C32, C33, C34, C35, C37, C38, C39, C42, C46, C47, C49, C50) in the Turkey Lakes Watershed (TLW) near Sault Ste. Marie in central Ontario; 16 (CN1, RC1, RC2, RC3, RC4, BC1, DE5, DE6, DE8, DE10, DE11, CB1, CB2, HP4, HP5, PC1) in the Dorset Lakes Area (DLA) near Dorset in eastern

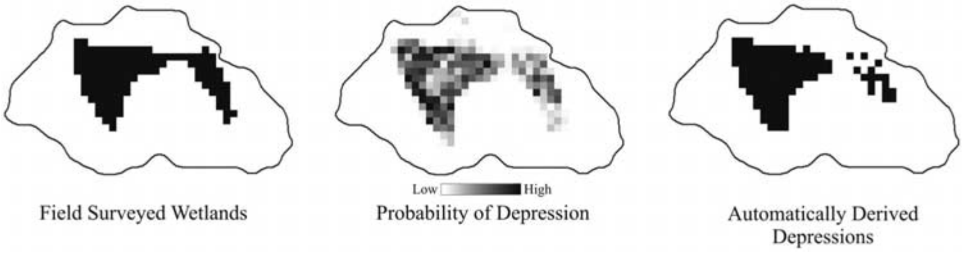

Figure 4. Spatial comparison of field surveyed wetlands with automatically derived wetlands based on applying a threshold to the p_{dep} image.

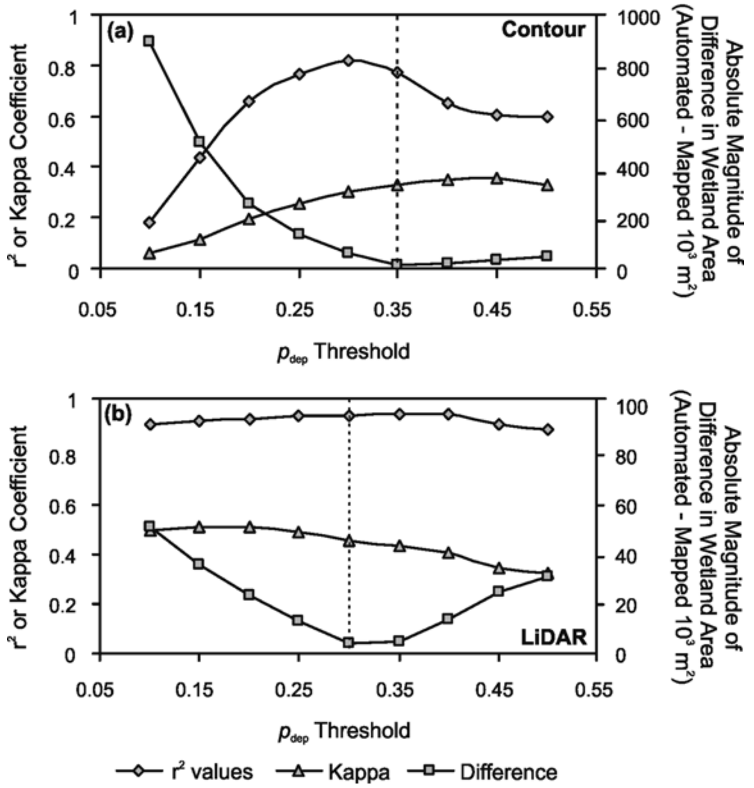

Figure 5. Statistical comparison of mapped wetlands with automatically derived wetlands based on applying a threshold to the p_{dep} image for the Turkey Lakes Watershed (TLW): (a) based on the 10 m contour digital elevation model (DEM); and (b) based on the 10 m light detection and ranging (LiDAR) DEM.

Ontario; and 1 (MPB) in Kejimkujik National Park (KEJ) in Atlantic Canada. The DOC records vary in duration among the catchments (Figure 2). A common period (1989–1997) was selected for the analyses conducted in this study. A detailed summary of the terrestrial ecozones, ecoregions and ecodistricts, average annual temperature and precipitation (from 1989 to 1997), geology, topography, soils and forest type for the catchments is provided in Table 1.

3. Methods

3.1. Mapping Wetlands

[8] Digital topographic data from aerial photography with contours at a scale of 1:10,000 (5 m contour interval) or 1:20,000 (10 m contour interval) and including spot heights, lakes, and streamlines were obtained from provincial topographic series. DEMs were constructed using Australian National University Digital Elevation Model (ANUDEM) (version 5.2, 2006). A spline interpolation with a hydrologic drainage enforcement algorithm was used to ensure hydrologically correct DEMs (10 m) following the procedures outlined by *Hutchinson* [1989]. The optimal grid resolution for the DEMs was determined on the basis of the root mean square slope criterion [*Hutchinson*, 1996]. This criterion involves iteratively creating successively finer resolution DEMs and calculating the root mean square error between the slopes of the grids versus the source data at each resolution, and then identifying the grid resolution where refinements to the DEM resolution produce no significant increase in the root mean square slope of the DEM. For each DEM, pits and depressions were removed and a recursive D8 algorithm was used to identify each grid cell that drained

Table 2. A Comparison of Catchment and Wetland Areas Derived by Digital Terrain Analysis of Contour DEMs, LiDAR DEMs, and Field Mapping in the Experimental Catchments of the Turkey Lakes Watershed[a]

	Catchment Area (km^2)			Wetland Area (km^2)		
Catchment	Contour	LiDAR	Field	Contour	LiDAR	Field
C31	0.048	0.055	0.050	0.003	0.001	0.001
C32	0.058	0.066	0.067	0.000	0.001	0.001
C33	0.221	0.259	0.256	0.000	0.001	0.001
C34	0.708	0.694	0.691	0.025	0.005	0.008
C35	0.036	0.036	0.054	0.001	0.001	0.000
C37	0.158	0.158	0.158	0.037	0.020	0.019
C38	0.067	0.065	0.065	0.015	0.012	0.012
C39	0.178	0.170	0.174	0.004	0.007	0.003
C42	0.180	0.189	0.193	0.008	0.014	0.012
C46	0.440	0.431	0.431	0.017	0.003	0.006
C47	0.046	0.035	0.035	0.002	0.000	0.000
C49	0.157	0.145	0.144	0.008	0.004	0.003
C50	0.071	0.100	0.100	0.003	0.010	0.007
Total Area	2.366	2.400	241.83	0.121	0.079	0.072

[a]DEM, digital elevation model. LiDAR, light detection and ranging.

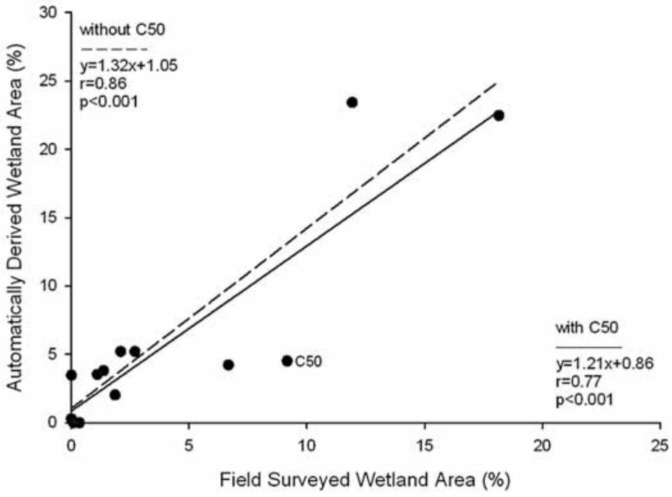

Figure 6. Relationship between field surveyed wetlands and automatically derived wetlands using the 10 m contour DEM for the TLW. Note: when C50 was excluded from analysis the r^2 increased from 0.77 to 0.86.

into the grid cell identified as the catchment outlet. The total area of the catchment was then calculated by taking the total number of grid cells draining into the catchment outlet and multiplying this number by the area of a single grid cell (i.e., 100 m^2).

[9] The TLW experimental catchments were used to develop the automated methods for deriving wetlands in catchments because we were able to compare automatically derived wetlands to field surveyed wetlands. For the TLW, we had access to DEMs obtained from aerial photography at a scale of 1:20,000 (10 m contour interval) and light detection and ranging (LiDAR) technology at a grid resolution of 2.5 m that was then coarsened to 10 m grid resolution using a bilinear resampling algorithm to be comparable with the contour DEM. This enabled us to explore the effects of the source of digital topographic data on wetland mapping. Digital terrain analyses were conducted on both the contour DEM and the LiDAR DEM to explore the effects of DEM quality on wetland mapping.

[10] At the TLW, field surveying of wetlands took a multiperson field crew 12 weeks to mark the boundaries of wetlands within the 13 experimental catchments, which represents a small fraction of the 10.5 km^2 watershed. Each catchment was surveyed on foot and the perimeters of surface or near surface saturated areas were flagged in June 2000. These perimeters were then geographically referenced using a differential GPS with decimeter precision under closed canopy (Leica GPS System 500). The GPS data were then mapped onto a 10 m LiDAR DEM and wetland areas determined by the total number of grid cells in the wetland boundary multiplied by the area of the grid cell.

[11] A much less labor-intensive process was used for automated mapping of wetlands (Figure 3) employing a probabilistic approach to map depressions and flats [*Lindsay and Creed*, 2005]. This approach recognizes that DEMs contain elevation errors and that a depression or flat is likely to exist if the "real" topographic difference between neighboring grid cells (i.e., the signal) is greater than the topographic error (i.e., the noise). A random elevation error term was added to the DEM, depressions in the DEM were filled [*Planchon and Darboux*, 2001], and each grid cell modified by the depression filling process was flagged. This process was repeated using different random elevation error terms selected from a distribution with a mean of zero and a standard deviation equal to the vertical accuracy of the DEM (LiDAR = 0.3 m, contour = 3 m). A probability of occurrence of a depression or flat was calculated by the number of times each grid cell is identified as a depression or flat (p_{dep}). This process was continued until the root mean square difference between p_{dep} images in two consecutive realizations was <0.001, indicating that the p_{dep} image was stable. A map was then produced with values ranging from 0 (areas with no probability of being a depression) to 1 (areas with 100% probability of being a depression) (Figure 4).

[12] Depressions and flats were defined as grid cells greater than a critical p_{dep} threshold and were subsequently classified as wetlands. The critical p_{dep} threshold was determined by optimizing the probability of wetland occurrence with those observed in the field. A series of wetland maps was generated using incremental increases of 0.05 from p_{dep} 0 to 1. Each wetland map was processed with a sieve filter to remove holes within homogenous areas classified as depressions and/or flats. This step is of particular importance in high data density DEMs (e.g., LiDAR) in which elevation differences of hummocks and hollows within a wetland may be larger than the elevation error term. The automatically derived wetland map was then compared to the field surveyed wetland map, both in terms of total wetland areas (m^2) using regression analysis and degree of coincidence of wetlands (%) using the Kappa coefficient of agreement. The critical threshold in p_{dep} was selected on the basis of the highest coefficient of determination and Kappa statistic between automatically derived and field surveyed wetlands. Critical p_{dep} thresholds of ≥ 0.35 for the 10 m contour DEM (Figure 5a) and ≥ 0.3

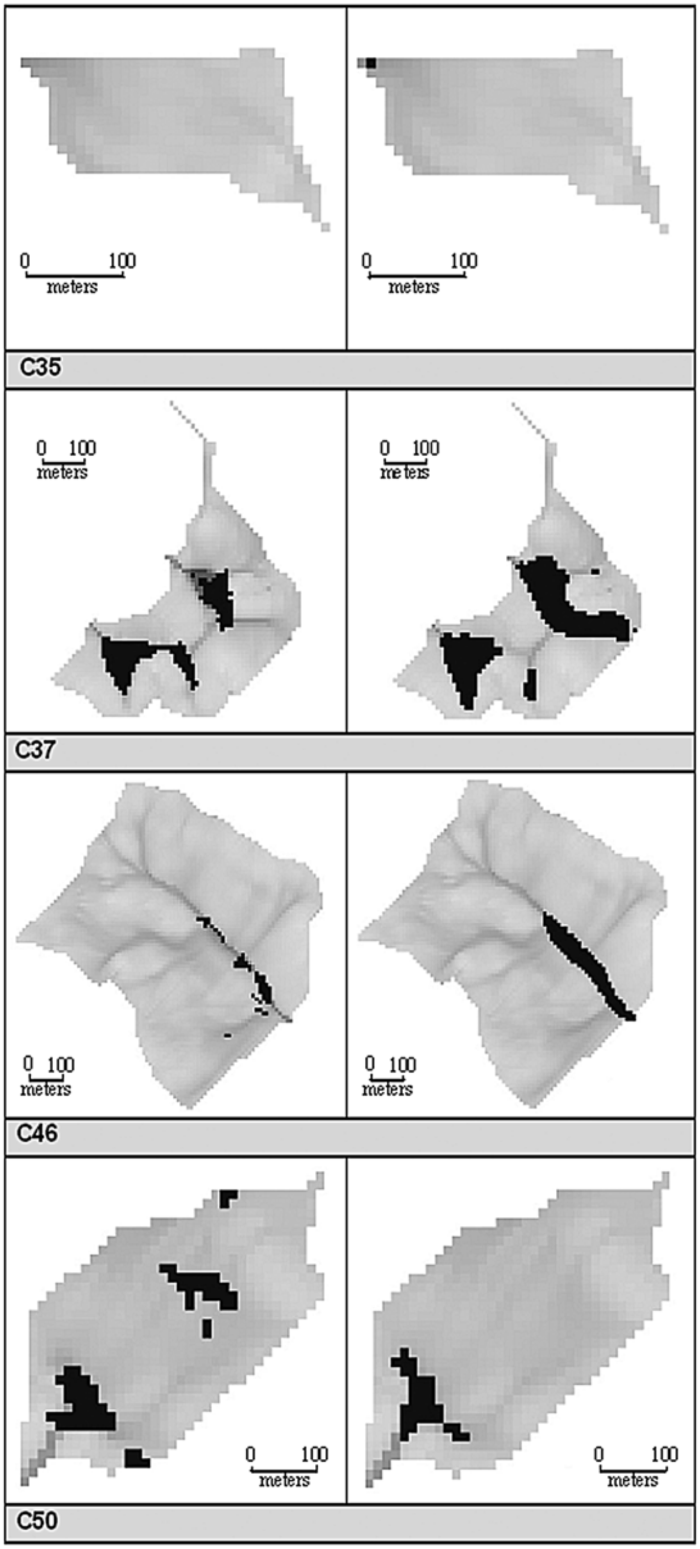

Figure 7. Map of (left) field surveyed and (right) automatically derived wetlands from the contour DEM for upland versus wetland-dominated catchments of the TLW. Wetlands are draped over maps of the topographic index [*Beven and Kirby*, 1979], which provides an indication of topographically controlled wetlands within each catchment. Small TI values (relative dry) are light grey areas, and large TI values (relatively wet) are dark grey areas.

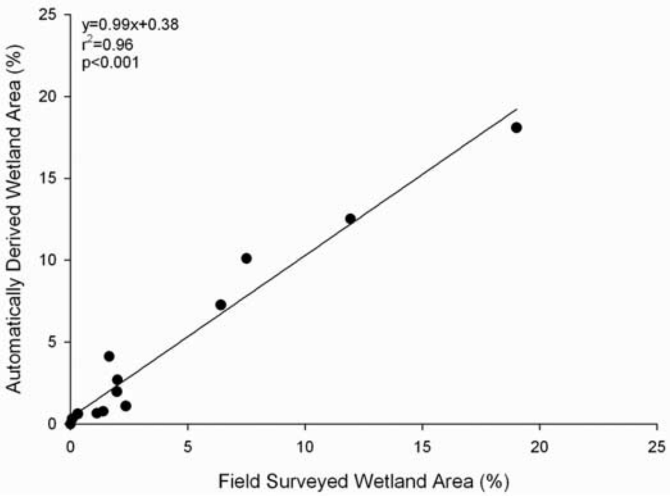

Figure 8. Relationship between field surveyed wetlands and automatically derived wetlands using the 10 m LiDAR DEM for the TLW.

for the 10 m LiDAR DEM (Figure 5b) were selected. The ≥ 0.35 critical p_{dep} threshold was then applied to the DEMs for the other regions and the proportions of wetlands within the catchments calculated.

[13] All GIS analyses were performed using the Terrain Analysis Software (Version 2.07) [*Lindsay*, 2005].

3.2. Measuring DOC Export

[14] Discharge for all streams was determined from continuous recordings of stream stage at weirs installed on the streams and converted to discharge from stage-discharge relationships. Stream samples for DOC analysis were collected on weekly or biweekly intervals with more frequent sampling during spring snowmelt and autumn storm events. DOC samples were filtered (except for KEJ and DLA), dissolved inorganic carbon (DIC) was removed by purging after acidification, and DOC was converted to DIC by persulfate oxidation catalyzed by UV (TLW, DLA) or heating to 102°C (ELA). The resulting DIC was converted to CO_2 by acidification and measured by infrared absorbance (ELA) or colorimetry (TLW, DLA). DOC Samples from KEJ were analyzed by high-temperature catalytic oxidation with an Ionics model 555 analyzer. While the protocols for DOC analysis varied across laboratories for each region, routine interlaboratory comparisons showed no significant differences in DOC concentrations.

[15] Daily stream DOC concentrations were generated by linear interpolation between sampling dates. DOC flux (g C/a) was calculated as the product of daily DOC concentration and daily discharge and summed for the water year (1 June to 31 May) before being normalized by catchment area. Average annual DOC export (and coefficient of variation) for each region for the study period was calculated.

3.3. Wetlands Versus DOC Export Models

[16] Regression analyses were conducted to relate wetlands to DOC export. In addition, indices were developed to capture regional differences in climatic conditions. Runoff coefficients were used to estimate the relative proportion of precipitation available for runoff versus the proportion lost to evapotranspiration and groundwater (e.g., a runoff coefficient of 1 means all precipitation goes to runoff). Growing degree days (with a base temperature of 10°C) were used to estimate the rate of decomposition of soil organic matter and production of DOC. Both climatic indicators were evaluated at an annual time frame (water year) from meteorological data readily available from Environment Canada. Multiple linear regressions were used to relate wetlands and climatic indicators to DOC export. Prior to the regression analyses, data were tested for normality, constant variance, and independence of residuals; none of the data required transformation. Regression analyses were performed using Sigma Stat (Statistical Package for the Social Sciences (SPSS), Incorporated, 1997, Sigmastat for Windows, Version 2.03).

4. Results

4.1. Mapping Wetlands

[17] In the TLW region, which was used to develop the automated method for mapping wetlands, the proportion of wetlands ranged from 0 to about 19% among the experimental catchments (Table 2). Wetlands varied from being small isolated areas (e.g., C35 and C47), to large contiguous wetlands (e.g., C37, C38, C42, C50). In most cases, the wetland drainage points were not coincident with the catchment drainage outlet. This indicates that if these wetlands were the sources of exported DOC, then the DOC exported from the wetlands moved along surface drainage pathways to the streams.

[18] A comparison of the proportion of wetlands determined from field surveyed versus automatically derived using digital terrain analysis was conducted on the contour DEM (Figures 6 and 7). There was a significant relationship between field and automatically derived wetlands ($r^2 = 0.77$, $p < 0.001$); when an outlier (C50) was removed the coefficient of determination increased from 0.77 to 0.86 (Figure 6). The spatial coincidence of wetlands was variable

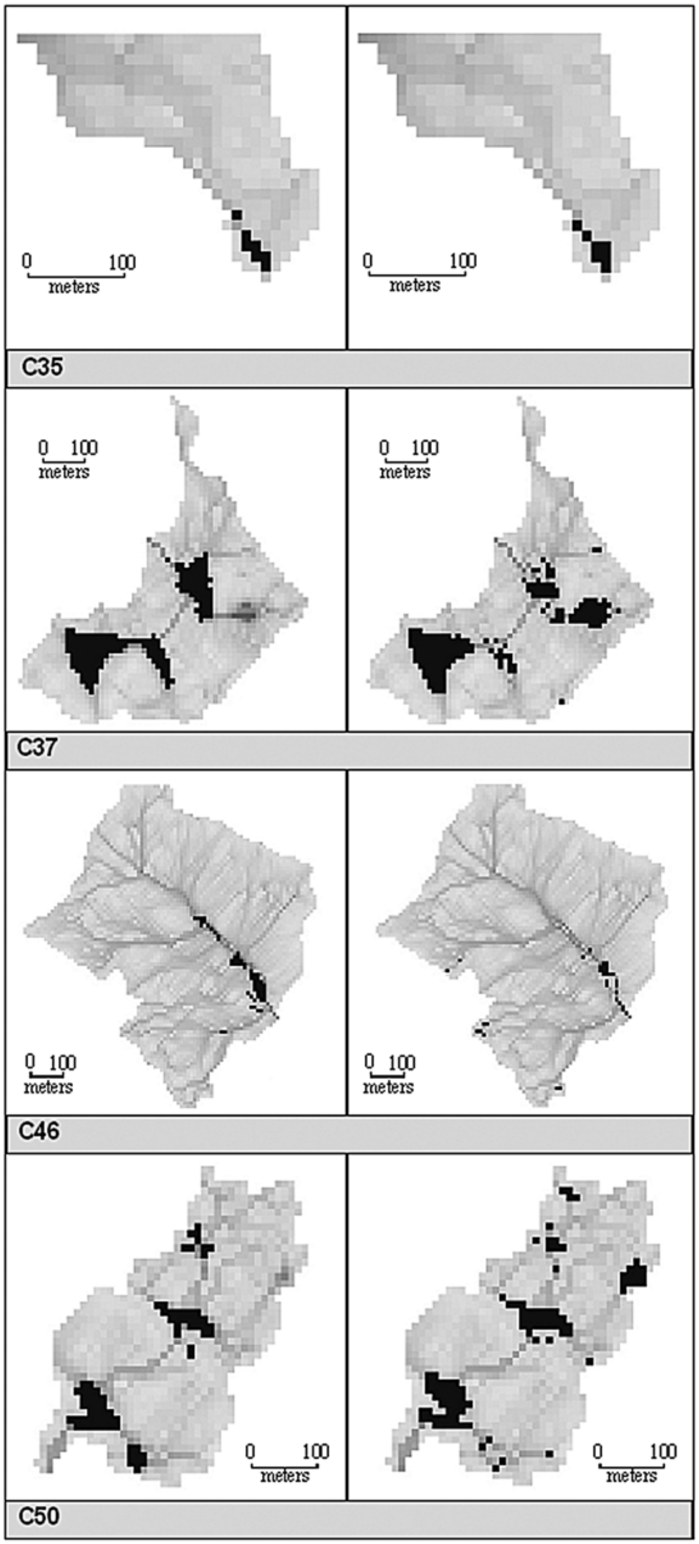

Figure 9. Map of field surveyed (left) and automatically derived (right) wetlands from the LiDAR DEM for upland versus wetland-dominated catchments of the TLW. Wetlands are draped over maps of the topographic index [*Beven and Kirby*, 1979], which provides an indication of topographically controlled wetlands within each catchment. Small TI values (relatively dry) are light grey areas and large TI values (relatively wet) are dark grey areas.

Table 3. Average Annual DOC Export for the Study Sites (1989–1997)[a]

Study Site	Catchment	Catchment Area (km^2)	Wetland Area (%)	Average Annual Runoff (mm)	Average Annual DOC Export (g $C/m^2/a$)
ELA[b]	E	1.66	19.23	427	5.39
	NE	0.17	34.27	362	6.90
	NW	0.55	12.59	488	4.65
Regional average		0.79	22.03	427	5.65
Coefficient of variation		0.98	0.50	0.15	0.20
TLW	C31	0.05	5.20	558	1.32
	C32	0.06	0.00	521	1.19
	C33	0.22	0.00	486	1.33
	C34	0.71	3.53	630	1.32
	C35	0.04	0.28	713	1.59
	C37	0.16	23.41	625	3.13
	C38	0.07	22.47	572	4.28
	C39	0.18	2.03	512	1.53
	C42	0.18	4.22	502	2.13
	C46	0.44	3.81	692	1.71
	C47	0.05	3.46	394	0.90
	C49	0.16	5.21	638	1.63
	C50	0.07	4.51	993	4.26
Regional average		0.18	6.01	603	2.03
Coefficient of variation		1.04	1.29	0.24	0.56
DLA	BC1	0.17	4.76	469	1.16
	CB1	0.45	31.04	575	3.58
	CB2	1.25	38.86	544	7.78
	CN1	4.42	48.18	543	4.89
	DE5	0.17	36.35	915	10.92
	DE6	0.33	42.77	362	5.75
	DE8	0.64	26.40	586	7.30
	DE10	0.73	29.30	563	7.41
	DE11	0.94	54.53	416	7.61
	HP4	1.25	24.55	516	3.02
	HP5	1.90	26.19	599	5.93
	PC1	0.23	23.88	542	5.38
	RC1	1.45	14.49	486	1.99
	RC2	0.20	23.26	716	9.46
	RC3	0.76	19.28	562	4.72
	RC4	0.46	18.39	595	4.27
Regional Average		0.96	28.89	562	5.70
Coefficient of Variation		1.10	0.44	0.22	0.46
KEJ	MPB	17.84	53.77	849	13.74

[a] All values are based on digital terrain analysis of 10 m contour DEMs.

[b] In ELA, catchment 239 had a fire that occurred in 1974 and again in 1980 which burned the eastern (E) catchment (Beaty, 1994), but a comparison of dissolved organic carbon (DOC) export ($g/m^2/a$) from the E, NE, and NW catchments suggest that the fire had no lasting effect on DOC export during our study period (1989–1997).

and largely dependent on the complexity of the terrain. Large wetlands found within catchments with little relief and/or concave topography (e.g., C37) were more successfully captured than small wetlands in catchments with steep and/or convex topography (e.g., C46) (Figure 7). C50 may have been an outlier because the uppermost wetland complex in C50 was not automatically detected resulting in an underestimation of the proportion of wetlands in C50 (see Figure 7, bottom). One explanation for the missing wetland is that it could have been removed during the process of interpolating the contour intervals. Much of this wetland sits on a narrow topographic bench that is about 20 m wide. This wetland could have been eliminated during the inter-

Table 4. Regression Models and Summary Statistics Based on Catchments for All Regions[a]

Regression Model	Exclusions	Adj r^2	p	SEE
DOC = 1.384 + (0.155 × % wetlands)		0.631	<0.001	1.905
DOC = 1.185 + (0.167 × %wetlands)	CN1, RC1–4	0.732	<0.001	1.675
DOC = ∼87.020 + (0.153 × % wetlands) + (0.0967 × GDD10)		0.676	<0.001	1.784
DOC = ∼95.441 + (0.165 × % wetlands) + (0.106 × GDD10)	CN1, RC1–4	0.796	<0.001	1.461
DOC = ∼4.153 + (0.147 × % wetlands) + (11.036 × RC)		0.786	<0.001	1.451
DOC = ∼3.701 + (0.160 × % wetlands) + (9.794 × RC)	CN1, RC1–4	0.861	<0.001	1.208
DOC = ∼63.736 + (0.146 × % wetlands) + (0.0656 × GDD10) + (10.133 × RC)		0.805	<0.001	1.385
DOC = ∼72.598 + (0.160 × % wetlands) + (0.0759 × GDD10) + (8.585 × RC)	CN1, RC1–4	0.893	<0.001	1.059

[a] Summary statistics are adjusted r^2 (adj r^2), p value, and standard error of the estimate (SEE).

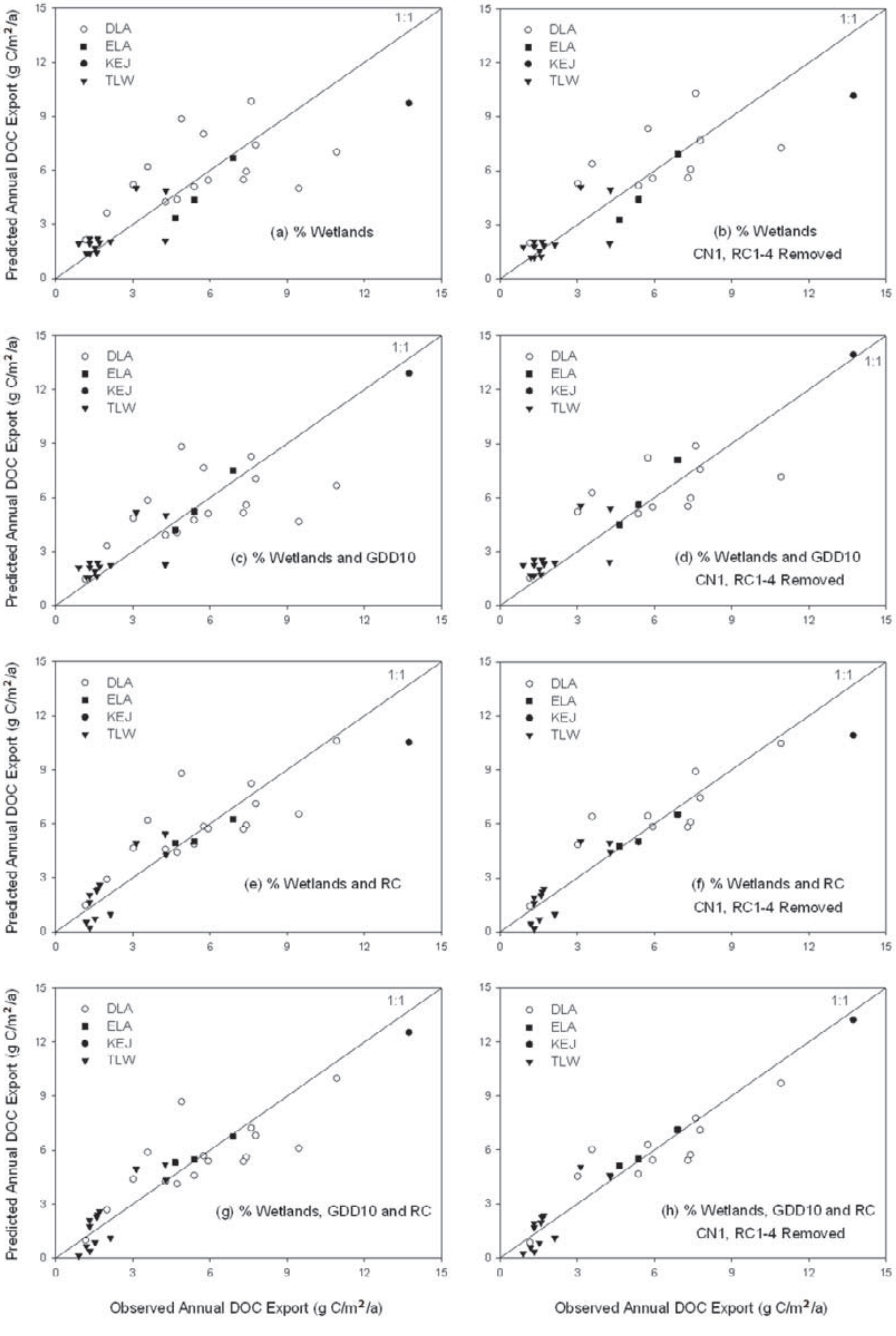

Figure 10. Predicted versus observed annual DOC export based on models developed from (a) % wetlands, (b) % wetlands excluding catchments CN1, RC1-4, (c) % wetlands and GDD10, (d) % wetlands and GDD10 excluding catchments CN1, RC1-4, (e) % wetlands and runoff coefficient (RC), (f) % wetlands and runoff coefficient excluding catchments CN1, RC1-4, (g) % wetlands, GDD10 and RC, and (h) % wetlands, GDD10 and RC excluding catchments CN1, RC1-4.

polation of the adjacent contours which occur at 10 m intervals.

[19] An additional comparison of field surveyed versus automatically derived wetlands was conducted on the LiDAR DEM (Figures 8 and 9). A stronger coefficient of determination was observed between field and automatically derived wetlands from the LiDAR DEM (Figure 8, r^2 = 0.96, p < 0.001). Furthermore, there were no outliers, suggesting that the LiDAR DEM was better able to capture wetland complexes on relatively steep slopes such as those that occur in C50 (Figure 9).

[20] An analysis of covariance showed no significant difference from the theoretical 1:1 line in the relationships of field surveyed versus automatically derived wetlands (including C50) for the contour DEM (for slope, F = 3.505, p = 0.075; for intercept, F = 3.920, p = 0.060) or the LiDAR DEM (for slope, F = 0.000, p = 0.984; for intercept, F = 0.271, p = 0.607).

4.2. Measuring DOC Export

[21] There was substantial regional and local spatial heterogeneity in average annual runoff, ranging from the lowest in the westernmost catchments at ELA with a regional average of 427 mm (coefficient of variation 0.15), to moderate at TLW with a regional average of 603 mm (coefficient of variation 0.24) and DLA with a regional average of 562 mm (coefficient of variation 0.22), to the highest in the easternmost catchment at KEJ with a regional average of 849 mm.

[22] There was also substantial spatial heterogeneity in the DOC export with average annual DOC export ranging from 0.90 g C/m^2/a from C47 at TLW to 13.74 g C/m^2/a from MPB at KEJ (Table 3). There was no systematic change in DOC export from the catchments across the glaciated landscape. Starting from the westernmost region, the average annual DOC export for ELA was 5.65 g C/m^2/a (coefficient of variation = 0.20), 2.03 g C/m^2/a for TLW (coefficient of variation = 0.56), 5.70 g C/m^2/a for DLA (coefficient of variation = 0.46), and 13.74 g C/m^2/a for KEJ. These statistics illustrate the substantial spatial heterogeneity in average annual DOC export both within and among the regions.

4.3. Wetlands Versus DOC Export Models

[23] A significant correlation was observed between proportion of wetlands and average annual DOC export (r^2 = 0.63, p < 0.001; Table 4). Several of the catchments in the Dorset region (i.e., CN1, RC1, RC2, RC3 and RC4) had open canopy wetlands (>5% of catchment area) near the catchment outlets that could have had a major effect on DOC export from the catchment. When these catchments were removed from the regression analyses, the coefficient of determination increased by 10% from 0.63 to 0.73. When the number of growing degree days with a base temperature of 10°C (GDD10) was added to the regression model the coefficient of determination increased from 0.73 to 0.80. When the runoff coefficient (RC) was added to the regression model, the coefficient of determination increased from 0.73 to 0.86. When both GDD10 and RC were added to the regional model, the coefficient of determination increased from 0.73 to 0.89 (Table 4). A comparison of predicted versus observed DOC export (Figure 10h) shows the model to be unbiased (i.e., follows the 1:1 line).

5. Discussion

[24] Wetland area within catchments has been found to be a major control over both drainage water DOC concentration [*Eckhardt and Moore*, 1990; *Gergel et al.*, 1999] and loadings to surface waters [*Clair et al.*, 1994; *Dillon and Molot*, 1997; *Creed et al.*, 2003]. However, mapping of forested wetlands can be a nontrivial task as they can occur both within canopy openings and underneath closed canopies. Field surveys of forested wetlands are not practical as they are time consuming and costly. This study uses recent developments in digital terrain analyses (DTA) to map both open and closed canopy wetlands and then explores if these computer generated wetlands can be used to model average annual DOC loading to surface waters across a broad geographic range of experimental catchments in the forests of eastern Canada.

[25] Previous efforts have been made on development of DTA for detection of wetlands. In an earlier, related study, *Creed et al.* [2003] used a deterministic approach based on a critical threshold in slope (1.75 degrees) below which a grid cell was classified as a wetland. *Creed et al.* [2003] found that application of this method on contour DEMs produced mediocre results for experimental catchments of the Turkey Lakes Watershed. A regression analysis of the relationship between proportion of field surveyed versus automatically derived wetlands generated a coefficient of determination of 0.63 (p < 0.01), and a regression analysis of the relationship between automatically derived wetlands versus average annual DOC export generated a coefficient of determination of only 0.42 (p < 0.05). Therefore, we explored an alternative to the slope threshold method with the goal of improving the performance of contour DEMs since these are the most widely available from government agencies.

[26] In this study, we used a stochastic modeling approach to identify wetlands in the experimental catchments of the Turkey Lakes Watershed. The stochastic modeling approach performed better than the slope threshold method presented by *Creed et al.* [2003]. The coefficient of determination for the relationship between the proportion of field surveyed versus automatically derived wetlands increased from 0.63 to 0.77 (Figure 5). A single outlier catchment (C50) affected the new results; when the single outlier was removed, the coefficient of determination increased an additional 13% up to 0.86. This single outlier revealed a potential limitation of conducting DTA on contour DEMs on forested landscapes. In forested catchments with many topographic benches where organic matter can accumulate, either finer-scale contour intervals or higher-density LiDAR data are needed to represent the topography. Both the deterministic approach used by *Creed et al.* [2003] and the stochastic approach used in this study were better able to predict depressions using LiDAR data rather than provincial topographic data. Thus, where LiDAR data are available, wetlands will be mapped more accurately.

[27] When we applied the stochastic modeling approach to contour DEMs across the glaciated landscape, we found that the proportion of wetlands within a catchment was able to explain the majority (63%) of the variation in DOC export. These experimental catchments covered a substantial range in climatic conditions, including a range in annual average temperature from 2.6 to 6.3°C and total annual precipitation range from 700 to 1400 mm. Previous studies have reported the potential for temperature driven changes in DOC export [e.g., *Clair and Ehrman*, 1996; *Worrall et al.*, 2004]. Temperature does not control production rates, but it does control consumption rates, and thereby may control the DOC pool available for export [*Moore and Dalva*, 2001]. Temperature may also control decomposition rates by regulating the level of microbial activity [*Pietikäinen et al.*, 2005] and/or phenol oxidase activity [*Freeman et al.*, 2001]. Addition of a temperature index (GDD10) to the regional DOC export model resulted in an additional explanation of variation by about 5%. This increase in the explanation of variation was due to an increase in the predictive capability across regions, as temperature was constant within each region.

[28] Previous studies have also reported the potential for hydrologic driven changes in DOC export from terrestrial and wetland areas to streams and lakes [e.g., *Worrall and Burt*, 2007; *Harrison et al.*, 2008]. Decreases in precipitation and/or increases in evapotranspiration reduce runoff and in turn decrease the transport of DOC [*Worrall and Burt*, 2007; *Harrison et al.*, 2008]. Addition of a runoff coefficient (RC) to the regional DOC export model resulted in an additional explanation of about 15% of the variance in DOC export. Where addition of a temperature index increased the predictive capability across the regions, addition of the runoff coefficient increased variance explanation due to the intraregional variations in runoff.

[29] Inclusion of both GDD10 and RC in a multiple linear regression model accounted for about 80% of the variation in DOC export. These results support the idea that both temperature and runoff play a significant role in regulating DOC export.

[30] Forested wetlands do not all behave as sources of DOC. Open canopy wetlands, including bogs and fens, and open water bodies within mainly forested catchments may decrease DOC export because of a combination of sedimentation, exposure to photolyzing radiation, microbial activity, and flocculation processes [*Curtis and Schindler*, 1997; *Schindler et al.*, 1997]. For example, *Dillon and Molot* [1997] excluded experimental catchments with bogs/fens near the catchment outlet when they developed their percent wetland–DOC relationship for the Dorset Lake Area. When we excluded these same experimental catchments from our final multiple linear regression model we were able to increase the explanation of variation from 80% to almost 90% (Table 4).

[31] The next generation of DOC export models will need to incorporate additional terms that represent wetlands with different functions with respect to carbon cycling and DOC export especially if these functions are sensitive to climate change. In areas that become drier, open canopy wetlands (such as the ones excluded from the DLA region) may start to dry up and switch from DOC sinks to DOC sources and increase DOC export. Alternatively, in areas that become wetter, wetlands that are transiently inundated may become permanently inundated and switch from DOC sources to DOC sinks and decrease DOC export. Additional research on the effect of inundated wetlands on DOC export with changing climate will yield further insight into this hypothesis.

6. Conclusions

[32] The purpose of this study was to determine whether or not a simple but robust model could be developed that predicts DOC loading to surface waters across a broad range of experimental catchments on forested landscapes on the glaciated landscape. We found that both open and closed canopy wetland areas could be mapped accurately using digital terrain analysis of readily available provincial topographic data. These wetland maps, combined with climatic indicators reflecting production of DOC (i.e., growing degree days above 10°C) and transport of DOC via runoff generating pathways (i.e., runoff coefficient), predicted 89% of the variance in average annual DOC loadings to surface waters among 33 experimental catchments. The digital terrain analysis approach used in this study performed well when mapping wetlands using 1:10,000 or 1:20,000 contour DEMs, but performed better when using light detection and ranging (LiDAR) spot height based DEMs. We provide a method for producing accurate estimates of average annual DOC loading to surface waters that is important given the role of DOC in the regulation of the structure and function of aquatic ecosystems.

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References

Aitkenhead, J. A., D. Hope, and M. F. Billett (1999), The relationship between dissolved organic carbon in stream water and soil organic carbon pools at different spatial scales, *Hydrol. Process.*, *13*, 1289–1302, doi:10.1002/(SICI)1099-1085(19990615)13:8<1289::AID-HYP766>3.0.CO;2-M.

Beven, K., and M. J. Kirby (1979), A physically based, variable contributing area model of basin hydrology, *Hydrol. Sci. Bull.*, *24*, 43–69.

Clair, T. A., and J. M. Ehrman (1996), Variations in discharge and dissolved organic carbon and nitrogen export from terrestrial basins with changes in climate: A neural network approach, *Limnol. Oceanogr.*, *41*, 921–927.

Clair, T. A., T. L. Pollock, and J. M. Ehrman (1994), Exports of carbon and nitrogen from river basins in Canada's Atlantic Provinces, *Global Biogeochem. Cycles*, *8*, 441–450, doi:10.1029/94GB02311.

Creed, I. F., S. E. Sanford, F. D. Beall, L. A. Molot, and P. J. Dillon (2003), Cryptic wetlands: Integrating hidden wetlands in regression models of export of dissolved organic carbon from forested landscapes, *Hydrol. Process.*, *17*, 3629–3648, doi:10.1002/hyp.1357.

Curtis, P. J., and D. W. Schindler (1997), Hydrologic control of dissolved organic matter in low-order Precambrian Shield lakes, *Biogeochemistry*, *36*, 125–138, doi:10.1023/A:1005787913638.

Dillon, P. J., and L. A. Molot (1997), Effect of landscape form on export of dissolved organic carbon, iron, and phosphorus from forested stream catchments, *Water Resour. Res.*, *33*, 2591–2600, doi:10.1029/97WR01921.

Driscoll, C. T., V. Blette, C. Yan, C. L. Schofield, R. Munson, and J. Holsapple (1993), The role of dissolved organic carbon in the chemistry and bioavailability of mercury in remote Adirondack lakes, *Water Air Soil Pollut.*, *67*, 319–344, doi:10.1007/BF00478152.

Eckhardt, B. W., and T. R. Moore (1990), Controls on dissolved organic carbon concentrations in streams, southern Quebec, *Can. J. Fish. Aquat. Sci.*, *47*, 1537–1544.

Eshleman, K. N., and H. F. Hemond (1985), The role of organic acids in the acid-base status of surface waters at Bickford Watershed, Massachusetts, *Water Resour. Res.*, *21*, 1503–1510, doi:10.1029/WR021i010p01503.

Freeman, C., N. Ostle, and H. Kang (2001), An enzymatic 'latch' on a global carbon store, *Nature*, *409*, 1–149, doi:10.1038/35051650.

Gergel, S. E., M. G. Turner, and T. K. Kratz (1999), Dissolved organic carbon as an indicator of the scale of watershed influence on lakes and rivers, *Ecol. Appl.*, *9*, 1377–1390, doi:10.1890/1051-0761(1999)009[1377:DOCAAI]2.0.CO;2.

Harrison, A. F., K. Taylor, A. Scott, J. Poskitt, D. Benham, J. Grace, J. Chaplow, and P. Rowland (2008), Potential effects of climate change on DOC release from three different soil types on the northern Pennines UK: Examination using field manipulation experiments, *Global Change Biol.*, *14*, 687–702, doi:10.1111/j.1365-2486.2007.01504.x.

Hedin, L. O., J. J. Armesto, and A. H. Johnson (1995), Patterns of nutrient loss from unpolluted old-growth temperate forest: Evaluation of biogeochemical theory, *Ecology*, *76*, 493–509, doi:10.2307/1941208.

Hobbie, J. E., and R. G. Wetzel (1992), Microbial control of dissolved organic carbon in lakes: Research for the future, *Hydrobiologia*, *229*, 169–180.

Hutchinson, M. F. (1989), A new procedure of gridding elevation and stream line data with automatic removal of spurious pits, *J. Hydrol. Amsterdam*, *106*, 211–232, doi:10.1016/0022-1694(89)90073-5.

Hutchinson, M. F. (1996), A locally adaptive approach to the interpolation of digital elevation models, in paper presented at the Third International Conference Integrating GIS and Environmental Modeling, Natl. Cent. for Geogr. Inf. and Anal., Univ. of Calif., Santa Fe, N. M., 21–25 January.

Inamdar, S. P., and M. J. Mitchell (2006), Hydrologic and topographic controls on storm-event exports of dissolved organic carbon (DOC) and nitrate across catchment scales, *Water Resour. Res.*, *42*, W03421, doi:10.1029/2005WR004212.

Kalbitz, K., S. Solinger, J. H. Park, B. Michalzik, and E. Matzner (2000), Controls on the dynamics of dissolved organic matter in soils: A review, *Soil Sci.*, *165*, 277–304, doi:10.1097/00010694-200004000-00001.

Lindsay, J. B. (2005), The Terrain Analysis System: A tool for hydrogeomorphic applications, *Hydrol. Process.*, *19*, 1123–1130, doi:10.1002/hyp.5818.

Lindsay, J. B., and I. F. Creed (2005), Removal of artifact depressions from digital elevation models: Towards a minimum impact approach, *Hydrol. Process.*, *19*, 3113–3126, doi:10.1002/hyp.5835.

McGlynn, B. L., and J. J. McDonnell (2003), Role of discrete landscape units in controlling catchment dissolved organic carbon dynamics, *Water Resour. Res.*, *39*(4), 1090, doi:10.1029/2002WR001525.

McKnight, D. M., E. M. Thurman, R. L. Wershaw, and H. F. Hemond (1985), Biogeochemistry of aquatic substances in Thoreau's Bog, Concord, Massachusetts, *Ecology*, *66*, 1339–1352, doi:10.2307/1939187.

Moore, T. R., and M. Dalva (2001), Some controls on the release of dissolved organic carbon by plant tissues and soils, *Soil Sci.*, *166*, 38–47, doi:10.1097/00010694-200101000-00007.

Moore, T. R., N. T. Roulet, and J. M. Waddington (1998), Uncertainty in predicting the effect of climatic change on the carbon cycle of Canadian peatlands, *Clim. Change*, *40*, 229–246, doi:10.1023/A:1005408719297.

Moore, T. R., J. L. Bubier, and L. Bledzki (2007), Litter decomposition in temperate peatland ecosystems: The effect of substrate and site, *Ecosystems*, *10*, 949–963, doi:10.1007/s10021-007-9064-5.

Neff, J. C., and G. P. Asner (2001), Dissolved organic carbon in terrestrial ecosystems: Synthesis and a model, *Ecosystems*, *4*, 29–48, doi:10.1007/s100210000058.

Ogawa, A., H. Shibata, K. Suzuki, M. J. Mitchell, and Y. Ikegami (2006), Relationship of topography to surface water chemistry with particular focus on nitrogen and organic carbon solutes within a forested watershed in Hokkaido, Japan, *Hydrol. Process.*, *20*, 251–265, doi:10.1002/hyp.5901.

Pietikäinen, J., M. Pettersson, and E. Bååth (2005), Comparison of temperature effects on soil respiration and bacterial and fungal growth rates, *FEMS Microbiol. Ecol.*, *52*, 49–58, doi:10.1016/j.femsec.2004.10.002.

Planchon, O., and F. Darboux (2001), A fast, simple and versatile algorithm to fill the depressions of digital elevation models, *Catena*, *46*, 159–176, doi:10.1016/S0341-8162(01)00164-3.

Schiff, S. L., R. Aravena, S. E. Trumbore, M. J. Hinton, R. Elgood, and P. J. Dillon (1997), Export of DOC from forested catchments on the Precambrian shield of central Ontario: Clues from ^{13}C and ^{14}C, *Biogeochemistry*, *36*, 43–65, doi:10.1023/A:1005744131385.

Schindler, D. W., and P. J. Curtis (1997), The role of DOC in protecting freshwaters subjected to climatic warming and acidification from UV exposure, *Biogeochemistry*, *36*, 1–8, doi:10.1023/A:1005768527751.

Schindler, D. W., P. J. Curtis, S. E. Bayley, B. R. Parker, K. G. Beaty, and M. P. Stainton (1997), Climate-induced changes in the dissolved organic carbon budgets of boreal lakes, *Biogeochemistry*, *36*, 9–28, doi:10.1023/A:1005792014547.

Skully, N. M., and D. R. S. Lean (1994), The attenuation of ultraviolet light in temperate lakes, *Arch. Hydrobiol.*, *43*, 135–144.

Sobek, S., L. J. Tranvik, Y. T. Prairie, P. Kortelainen, and J. J. Cole (2007), Patterns and regulation of dissolved organic carbon: An analysis of 7,500 widely distributed lakes, *Limnol. Oceanogr.*, *52*, 1208–1219.

Tarnocai, C. (1980), Canadian wetland registry, in *Proceedings*, *Workshop on Canadian Wetlands*, edited by C. D. A. Rubec and F. C. C. Pollett, *Ecol. Class. Ser.*, *12*, pp. 9–30, Lands Directorate, Environ. Canada, Ottawa, Ont.

Thurman, E. M. (1985), *Organic Chemistry of Natural Waters*, 497 pp., Dordrecht, Boston.

Vitousek, P. M., L. O. Hedin, P. A. Matson, J. H. Fownes, and J. C. Neff (1998), Within-system element cycles, input-output budgets and nutrient limitation, in *Successes*, *Limitations and Frontiers in Ecosystem Science*, edited by P. M. Groffman and M. L. Pace, pp. 432–451, Springer, New York.

Webster, K. L., I. F. Creed, R. A. Bourbonnière, and F. D. Beall (2008), Controls on the heterogeneity of soil respiration in a tolerant hardwood forest, *J. Geophys. Res.*, *113*, G03018, doi:10.1029/2008JG000706.

Worrall, F., and T. P. Burt (2007), Flux of dissolved organic carbon from U.K. rivers, *Global Biogeochem. Cycles*, *21*, GB1013, doi:10.1029/2006GB002709.

Worrall, F., T. P. Burt, and J. Adamson (2004), Can climate change explain increases in DOC flux from upland peat catchments?, *Sci. Total Environ.*, *326*, 95–112, doi:10.1016/j.scitotenv.2003.11.022.

Xenopoulos, M. A., D. M. Lodge, J. Frentress, T. A. Kreps, S. D. Bridgham, E. Grossman, and C. J. Jackson (2003), Regional comparisons of watershed determinants of dissolved organic carbon in temperate lakes from the Upper Great Lakes region and selected regions globally, *Limnol. Oceanogr.*, *48*, 2321–2334.

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