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Cryptic wetlands: integrating hidden wetlands in regression models of the export of dissolved organic carbon from forested landscapes

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Abstract:

This study examines the relationship between wetlands hidden beneath the forest canopy ('cryptic wetlands') and dissolved organic carbon (DOC) export to streams and lakes in forested ecosystems. In the Turkey Lakes Watershed (TLW), located in the Algoma Highlands of central Ontario, Canada, there is substantial natural variation in average annual DOC export (kgC ha^{-1} year^{-1}), ranging from 11·4 to 31·5 kgC ha^{-1} year^{-1} in catchments with no apparent wetlands. We hypothesized that the natural variation in DOC export was related to cryptic wetlands. Cryptic wetlands were derived manually from geographic coordinates that were surveyed with a differential global positioning system, and automatically from identification of topographic depressions and flat slopes (<1·5°) within a digital elevation model (DEM) in a geographic information system. For the TLW catchments, which are characterized by shallow soils over bedrock, a significant correlation ($r^2 \geq 0{\cdot}9$, $p < 0{\cdot}001$) between manual and automated methods was observed for scales up to 50 m when a light detection and ranging DEM was used for the topographic analysis. Regression models indicated that cryptic wetlands (%) explained the majority of the natural variation in DOC export (kgC ha^{-1} year^{-1}), with $r^2 = 0{\cdot}88$ ($p < 0{\cdot}001$) for the model based on the manually derived wetlands and $r^2 = 0{\cdot}85$ ($p < 0{\cdot}001$) for the model based on the automatically derived wetlands. The strength and significance of the automatically derived wetlands (%) versus DOC export (kgC ha^{-1} year^{-1}) regression model diminished when other sources of DEMs were used. This study emphasizes the importance of including cryptic wetlands in predictive models of DOC export, particularly in catchments where the topography includes depressions and flat areas but no apparent wetlands. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS forest; wetland; DOC; digital terrain analysis; Turkey Lakes Watershed

INTRODUCTION

Wetlands are the principal source of dissolved organic carbon (DOC) to streams, rivers and ultimately lakes in forested ecosystems (e.g. Mulholland and Kuenzler, 1979; Urban *et al*., 1989; Eckhardt and Moore, 1990; Hemond, 1990; Koprivnjak and Moore, 1992; Kortelainen, 1993; Clair *et al*., 1994; Hope *et al*., 1994; Dillon and Molot, 1997; Mulholland, 1997; Gergel *et al*., 1999). In previous studies, the wetlands considered in DOC export models were typically bogs, fens and/or marshes. These wetlands often have distinctive canopy cover that can easily be detected by aerial photography or satellite imagery. However, in many forests, wetlands may consist of an assemblage of forested swamps that are hidden under forest canopy. We propose that these cryptic wetlands are important contributors to the DOC export from forested catchments.

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DOC, operationally defined as the organic carbon that passes through a 0·45 μm filter (Moore, 1998), 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). Compared with other fluxes of carbon, the flux of DOC to streams, rivers and lakes is small and, thus, it is often not considered to be an important component of the global carbon budget (Neff and Asner, 2001). However, the flux of DOC is important to the land–stream–lake ecosystem. For example, dissolved organic matter (DOM) provides an important energy source for aquatic communities downstream (Hobbie and Wetzel, 1992). Carbon, nitrogen, sulphur and phosphorus in DOM is exported from ecosystems, and, over long time scales, a reduction in the export of DOM containing essential elements can reduce the capacity of ecosystems to support primary productivity (Hedin *et al.*, 1995; Vitousek *et al.*, 1998; Neff and Asner, 2001). Trace metals and contaminants, adsorbed to DOM, are also exported from the system, influencing their exposure and toxicity to organisms (Thurman, 1985; Driscoll *et al.*, 1995). Changes in the rate of DOC loading affect the acid–base balance of aquatic systems (Eshelman and Hemond, 1985) and alter the penetration of UV-B (Schindler and Curtis, 1997), which may be harmful to aquatic organisms (Skully and Lean, 1994). The potential for changes in the relative importance of the flux of DOC to surface waters in response to changes in climate is not clearly understood (Moore *et al.*, 1998), with some studies projecting that the export of DOC from wetlands will double by 2050 (e.g. Clair *et al.*, 2002). Consequently, although the flux of DOC to surface waters represents a minor flux in the global carbon cycle, it is an important flux in the biogeochemistry of terrestrial and aquatic systems (Neff and Asner, 2001).

To understand the factors that control the flux of DOC, the hydrogeologic setting of a catchment must be considered. Fraser *et al.* (2001), synthesizing several studies, observed high rates of DOC export ($>$0·20 kgC ha^{-1} year^{-1}) in hydrogeologic settings that result in high runoff ($>$500 mm year^{-1}) resulting from precipitation $P \gg$ evapotranspiration (ET) or upland area $\gg$ wetland area. In contrast, low rates of DOC export ($<$0·10 kgC ha^{-1} year^{-1}) were observed in hydrogeologic settings that result in low runoff ($<$250 mm year^{-1}) resulting from $P \approx$ ET or wetland-dominated systems.

Within catchments with relatively high rates of DOC export, the presence of wetlands has been related to DOC export. Wetlands are defined as areas where the water table is at, near or above the ground surface for long enough periods of time to change the pedological and ecological properties of the area (Tarnocai, 1980; Price and Waddington, 2001). Over the past 15 years, many studies have reported a relationship between the proportion of wetlands in the contributing drainage area and the average annual *concentration* of DOC in streams (e.g. Urban *et al.*, 1989; Eckhardt and Moore, 1990; Hemond, 1990; Koprivnjak and Moore, 1992; Clair *et al.*, 1994; Hope *et al.*, 1994; Mulholland, 1997) and lakes (e.g. Kortelainen, 1993; Gergel *et al.*, 1999), and the annual average *flux* of DOC to streams (e.g. Mulholland and Kuenzler, 1979; Dillon and Molot, 1997).

For catchments on the Precambrian Shield, Dillon and Molot (1997) established a significant relationship between wetlands (specifically peatlands, %; i.e. open canopy and/or canopy with distinct canopy species) and DOC export (kgC ha^{-1} year^{-1}). However, for catchments reported to have no peatlands, the DOC export ranged from 9·9 to 32·8 kgC ha^{-1} year^{-1}. Resolution of this natural variation or 'noise' among catchments with no apparent wetlands may be important, as the Precambrian Shield is typified by aquatic systems where DOC loads could be disproportionately important to the trophic structure of the surface waters (Findlay and Sinsabaugh, 1999).

This study sought to test the hypothesis that cryptic wetlands (i.e. closed-canopy wetlands with no distinct wetland-specific canopy species, as indicated by analysis of aerial photography and/or satellite imagery) affect DOC export. The objective was to develop a regression model for predicting the export of DOC from apparently uniformly forested catchments within the Turkey Lakes Watershed (TLW), in the Algoma Highlands of central Ontario, Canada. More specifically, the objectives were: (1) to document the natural variation in DOC export from catchments; (2) to estimate the proportion of cryptic wetlands within the catchments, using both manually derived estimates from differential global positioning system (GPS) surveys and automatically derived estimates from geographic information system (GIS) technology, evaluating the influence of the scale and source of the digital elevation model (DEM) on the automatically derived estimates; and (3) to gain insight into the relationship between cryptic wetlands and DOC export from the catchments. This study represents our initial investigation towards a better understanding of the hydrologic regulation of DOC export dynamics within the region.

STUDY AREA

The TLW is a 10·5 km^2 experimental watershed centred at 47°03′N and 84°25′W, about 60 km north of Sault Ste Marie in the Algoma Highlands of central Ontario (Figure 1). The watershed contains a hydrologic

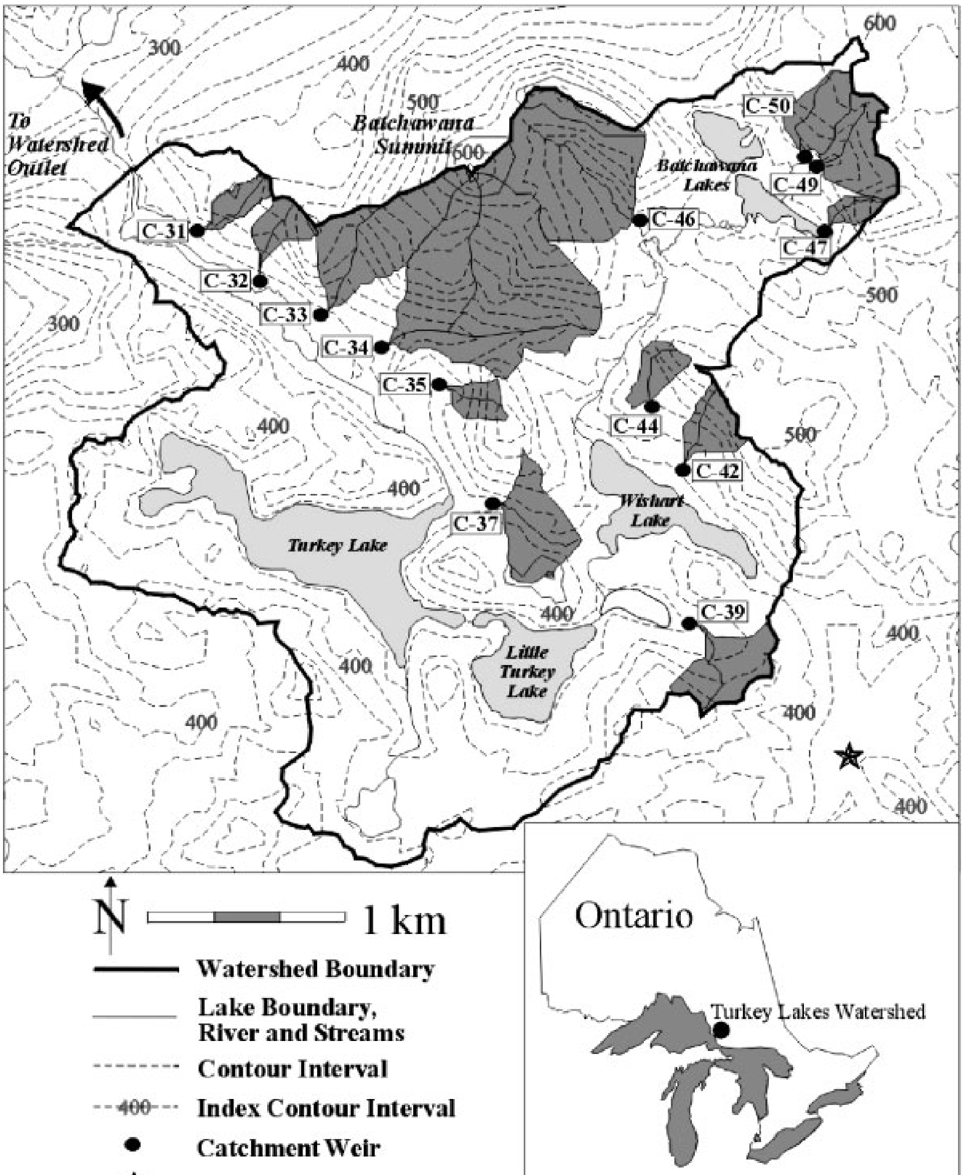

Figure 1. Location of the experimental catchments in the Turkey Lakes Watershed, in central Ontario, Canada

system of headwater catchments draining into a chain of lakes; eventually the hydrologic system drains into Batchawana Bay on the eastern shore of Lake Superior.

The climate is continental and is strongly influenced by Lake Superior. Peak discharge events in the watershed occur in late May, during the spring snow melts, and again in late September to early October, coinciding with autumn storms. The topography is controlled by the bedrock, with 410 m of relief from the outlet (at 243 m a.s.l.) to the summit of Batchawana Mountain (at 653 m a.s.l.). The bedrock is primarily Precambrian metamorphosed basalt (greenstone) with small outcrops of more felsic igneous rock (granite) near the main inflow to Little Turkey Lake (Semkin and Jeffries, 1983). Regional fault systems, occurring diagonally across the watershed (northwest–southeast and southwest–northeast), exhibit significant control over the angular drainage patterns (Semkin and Jeffries, 1988). Overlying the bedrock is a thin and discontinuous moraine of silty to sandy till, ranging from <1 m at higher elevations to 1–2 m at lower elevations (Jeffries and Semkin, 1982), although pockets of deep (up to 70 m) till deposits can occur in some fault lines and abrupt valleys in the bedrock that have been entirely filled in (Elliot, 1985). Within the till deposits, Orthic Ferro-Humic and Humo-Ferric podzolic soils have developed, with dispersed pockets of highly humified organic deposits (Ferric Humisols) found in bedrock-controlled depressions and adjacent to streams and lakes (Canada Soil Survey Committee, 1978; Cowell and Wickware, 1983). The TLW is covered by an uneven-aged mature forest composed of 90% sugar maple (*Acer saccharum* Marsh.), 7% yellow birch (*Betula alleghaniensis* Britton) and other minor species including red maple (*Acer rubrum* (L.)), ironwood (*Ostrya virginiana* (Mill.)) and white spruce (*Picea glauca* (Moench.)) (Wickware and Cowell, 1983, 1985). There are few wetlands in the TLW according to standard topographic maps of the region.

The TLW is the focus of research investigating the effects of acid precipitation and climate change on forested ecosystems (Jeffries, 2002). Hydrological and biogeochemical data for these catchments extend back to 1980, with a consistent data set for DOC and dissolved inorganic carbon (DIC) available from 1987 to the present. In the summer of 1997, a forest harvesting experiment, including selective, shelterwood and cutblock harvests, was initiated in three of the experimental catchments. This paper focuses on data collected prior to the initiation of the experiments, and therefore includes the water years (1 June to 31 May) from 1987 to 1996. Preceding this experimental harvest the watershed had been relatively undisturbed, with the exception of a small selective harvest for yellow birch in the 1950s.

METHODS

A regression model for the prediction of DOC export from forested catchments in the TLW was developed, where the predictor variable was the proportion of cryptic wetlands within each of the 12 experimental catchments and the response variable was DOC flux (kgC ha^{-1} $year^{-1}$).

Predictor variable

Manual (GPS) derivation of cryptic wetlands. The extents of the cryptic wetlands were manually demarcated using flags during ground surveys conducted in June 2000. Although both organic-rich mineral soil wetlands and organic soil (i.e. peat) wetlands were observed, there was no discrimination between these two types of wetland in this study. During these ground surveys, each catchment was traversed on foot and margins of surface or near-surface saturation were flagged as denoting the perimeter of post-melt wetlands. An area was considered to be a wetland if: (1) a surface water-mark was present, reflecting the former perimeter of a receding wetland; (2) a contiguous area of standing water was observed; (3) a contiguous area in which moderate pressure applied by a rubber boot forced gravimetric water from the soil was observed; (4) a surface slump was present, reflecting a change in subsurface soil properties from dry to wet conditions; and/or (5) an understory species or community representative of saturated or near-saturated soils was observed. The last two criteria were of particular importance in the demarcation of cryptic wetlands, as they show that these regions are not just transient, but rather reflect the saturation status of the soil in both wet and dry years. Afterwards, the margins of the wetlands were geographically referenced using a differential GPS with millimetre precision in open canopy conditions and decimetre precision in closed canopy conditions (Leica GPS System 500, Leica Geosystems Ltd, Willowdale, ON).

The GPS data were imported to a GIS program, Blackland GRASS (v. 1.992; BLG Research Center, Temple, TX), for geographic analysis. Contributing drainage areas for each catchment were extracted from a 2·5 m light detection and ranging (LiDAR) DEM created using airborne laser mapping technology. The GPS data for the wetlands were then overlayed on their respective catchments and the total area (m^2) and percentage area of wetlands were calculated.

Automatic (GIS) derivation of cryptic wetlands. Digital terrain analyses were conducted for wetland delineation within the DEM. Wetlands were identified as areas with topographic depressions and/or flat slopes. Topographic depressions were identified by computing the difference between a DEM with and without topographic depressions filled (Martz and Garbrecht, 1998); a positive value in the resultant map was identified as a topographic depression. Flat slopes were defined as those less than a threshold that was specified by optimizing the automatic (GIS) method with the manual (GPS) method of delineating wetlands. In the optimization, aspatial properties (i.e. total wetland (m^2) and percentage wetland) were evaluated using regression analysis (SigmaStat v. 2.03; SPSS Inc., Chicago, IL) and spatial properties were evaluated using a fuzzy criterion (IDRISI v. 3.2).

The fuzzy criterion (Zadeh, 1965) reported the coincidence between the automatically and manually derived wetlands (0 to 100%, where 0% is no membership and 100% is full membership). A fuzzy membership map was created using a monotonically decreasing sigmoidal function: direct coincidence with the manually derived wetland represented full membership, and $\geq$1000 m from the edge of the manually derived wetland represented no membership. Each grid of the automatically derived wetland map was assigned the value of the equivalent grid in the fuzzy membership map. The direct coincidence reported the percentage of the automatically derived wetland that coincided with the manually derived wetlands within each catchment. The fuzzy coincidence reported the percentage of the automatically derived wetlands that coincided within an area $\leq$100 m from the manually derived wetlands within each catchment.

DEMs of different scales and from different sources were used to evaluate the sensitivity of wetland delineation to the selected DEM. To test the effects of the *scale* of the LiDAR DEM on the prediction of wetlands, the LiDAR DEM grid was coarsened by using a nearest-neighbour algorithm, where the coarser grid is assigned the elevation of the centre of the square of the grids. The finest grids (i.e. 2·5 m) were used as the basis for scaling to coarser grids of 5, 10, 25, 50 and 100 m. To test the effects of the *source* of the DEM on the prediction of wetlands, four different DEMs were used, all of which were interpolated to a 5 m grid. The first DEM was derived from the LiDAR DEM (originally a 2·5 m DEM). The remaining DEMs were derived from photogrammetric analysis of aerial photographs at scales of 1 : 12 000 (collected specifically for the TLW research program), 1 : 50 000 interpolated to 1 : 20 000 (Ontario Base Map (OBM)) and 1 : 65 000 to 1 : 85 000 interpolated to 1 : 50 000 (National Topographic Series (NTS)). For each of these photogrammetrically derived DEMs, digital contours were interpolated to 5 m grids using the procedure outlined by Hutchinson (1989).

Response variable

For water flux estimates, precipitation data were collected from the main meteorological recording station located at the southeast boundary of the watershed and discharge data (mm day^{-1}) were collected from each of the experimental catchments within the watershed (Figure 1). Missing precipitation data were estimated by linear regression based on data from two nearby meteorological recording stations, Montreal Falls (47°15′N, 84°24′W) and Sault Ste Marie airport (46°29′N, 84°30′W). Missing discharge data (usually low flows during winter) were estimated by a simple linear regression with an adjacent catchment for which there was a complete record.

For estimates of the concentration (mgC l^{-1}) and flux (kgC ha^{-1} year^{-1}) of DOC, precipitation samples were collected weekly during the spring, summer and autumn and bi-weekly during the winter near the

TLW outflow. Discharge samples were collected daily during the spring snowmelt, weekly or bi-weekly during the summer and autumn, and bi-weekly during the winter. The *concentration* of DOC (mgC l^{-1}) was determined by filtering a 100 ml sub-sample through a 0·45 μm Pall GN-6 Metricel membrane filter, made from hydrophilic mixed cellulose esters, and then analysing the filtered samples within 48 h of collection on a Technicon Autoanalyser II using the potassium persulphate method (Crowther and Evans, 1978). The daily *flux* of DOC (kgC ha^{-1} day^{-1}) was calculated as the product of the total daily discharge and the interpolated daily concentration of DOC in the discharge. Interpolation was performed using a dynamic linear regression program, which interpolates missing values based on a running average of the two known values located directly before and directly after the unknown values. The annual *flux* of DOC (kgC ha^{-1} $year^{-1}$) was calculated as the annual sum of the daily fluxes based on the water year.

The established DOC sampling protocol was not ideal for investigations into hydrologic regulation of DOC export. DOC samples were collected on a daily basis during the spring melts and on a weekly basis during the autumn storms, both critical seasons for DOC export. Given the limitations of the DOC sampling protocol, we focused our analyses on the annual average concentration and flux of DOC from the catchments.

RESULTS AND DISCUSSION

DOC export characteristics

The degree of natural variation in DOC export characteristics was assessed from the average and the coefficient of variation (a measure of the dispersion about the average) of DOC export characteristics, both among years (average of catchments for each year) and among catchments (average of years for each catchment).

Inspection of the DOC budgets revealed substantial among-year variation in DOC fluxes (Table I). Over the 10 year record, the average input flux of water in precipitation was 1297 mm $year^{-1}$, ranging from 1113 to 1521 mm $year^{-1}$, and the average output flux of water in discharge was 591 mm $year^{-1}$, ranging from 463, 489 and 492 to 779 mm $year^{-1}$ (Table I). During this same 10 year record, the annual average input concentration of DOC was 0·99 mgC l^{-1}, ranging from 0·63 to 1·47 mgC l^{-1}, and the annual average output concentration of DOC was 2·97 mgC l^{-1}, ranging from 2·79 to 3·56 mgC l^{-1}. The coefficient of variation for the output concentration of DOC was large, ranging from 27·2 to 38·6% (Table I). The average input flux of DOC was 11·92 kgC ha^{-1} $year^{-1}$, ranging from 10·02 to 17·65 kgC ha^{-1} $year^{-1}$. This flux is higher than input fluxes reported west of TLW, in the Experimental Lakes Area, near Kenora, Ontario (i.e. 0·9 kgC ha^{-1} $year^{-1}$; Linsey *et al.*, 1987) and east of TLW, in the Dorset Lakes Area, near Dorset, Ontario (i.e. 8·7 kgC ha^{-1} $year^{-1}$; Dillon and Molot, 1997). The average output flux of DOC was 17·72 kgC ha^{-1} $year^{-1}$, ranging from 14·61 to 23·22 kgC ha^{-1} $year^{-1}$. This flux is towards the lower end of ranges found in studies within similar physiographic regions in central Ontario, including a study by Dillon and Molot (1997) that reported a flux of DOC to streams ranging from 9·90 to 90·8 kgC ha^{-1} $year^{-1}$ in the Dorset Lakes Area. As with the output concentration of DOC, the coefficient of variation for the output flux of DOC was large, ranging from 32·8 to 49·7% (Table I).

Inspection of the DOC budgets also revealed that the catchments were not uniformly responsive for the 10 year record (Table II). For most catchments, the concentrations and fluxes of DOC leaving the catchment were larger than those entering the catchment. However, there was substantial natural variation among the catchments in the magnitude of the DOC export characteristics. The catchment average discharge ranged from 471 to 761 mm $year^{-1}$, with the coefficient of variation ranging from 13·8 to 27·4%. The catchment average annual concentrations of DOC ranged from 2·11 to 5·04 mgC l^{-1} and the catchment average flux of DOC ranged from 11·36 to 31·49 kgC ha^{-1} $year^{-1}$. Catchments with the largest average concentrations and fluxes of DOC were c37, c42 and c50, having concentrations of 5·04 mgC l^{-1} $year^{-1}$, 4·24 mgC l^{-1} $year^{-1}$ and 4·00 mgC l^{-1} $year^{-1}$ and fluxes of 31·49 kgC ha^{-1} $year^{-1}$, 28·67 kgC ha^{-1} $year^{-1}$ and 22·52 kgC ha^{-1}

Table I. Temporal variability of the annual water and DOC budgets for the experimental catchments. For each year, the average and coefficient of variation (within parentheses) are based on data collected from the individual catchments

Year	Input			Output		
	Water (mm year^{-1})	DOC (mgC l^{-1})	DOC (kgC ha^{-1} year^{-1})	Water (mm year^{-1})	DOC (mgC l^{-1})	DOC (kgC ha^{-1} year^{-1})
1987	1239	1·01	11·65	463 (24·4)	3·56 (34·6)	19·64 (33·5)
1988	1521	1·23	17·65	779 (16·0)	3·09 (27·2)	23·22 (42·5)
1989	1161	1·47	15·39	489 (19·4)	3·03 (27·5)	14·61 (42·8)
1990	1254	1·00	11·12	550 (26·9)	2·81 (34·7)	15·80 (49·7)
1991	1293	0·95	11·70	618 (20·2)	3·08 (38·1)	18·68 (35·6)
1992	1345	0·74	10·30	626 (23·8)	2·81 (32·1)	17·48 (43·3)
1993	1374	0·63	10·30	657 (16·7)	2·79 (38·6)	18·39 (44·1)
1994	1113	0·99	10·02	492 (13·6)	2·93 (32·6)	14·61 (38·3)
1995	1293	0·93	10·44	586 (14·2)	2·83 (32·5)	16·69 (38·3)
1996	1375	0·91	10·58	650 (13·8)	2·81 (33·1)	18·07 (32·8)
Average	1297	0·99	11·92	591	2·97	17·72
Minimum	1113	0·63	10·02	463	2·79	14·61
Maximum	1521	1·47	17·65	779	3·56	23·22

Table II. Spatial variability of the annual water and DOC budgets for the experimental catchments. For each catchment, the average and coefficient of variation (within parentheses) are based on data collected for the water years 1987 to 1996

Catchment	Area (ha)	Input			Output		
		Water (mm year^{-1})	DOC (mgC l^{-1})	DOC (kgC ha^{-1} year^{-1})	Water (mm year^{-1})	DOC (mgC l^{-1})	DOC (kgC ha^{-1} year^{-1})
		1297 (9·0)	0·99 (23·7)	11·92 (21·4)			
c31	5·42				596 (27·4)	2·39 (9·3)	14·68 (22·8)
c32	6·42				496 (21·0)	2·48 (27·8)	12·07 (36·1)
c33	23·52				471 (19·9)	2·53 (10·3)	12·31 (16·3)
c34	68·80				693 (18·5)	2·11 (11·0)	14·20 (21·7)
c35	3·12				624 (13·8)	2·23 (10·0)	13·71 (12·0)
c37	15·34				631 (19·2)	5·04 (11·8)	31·49 (11·5)
c39	16·59				554 (23·1)	3·12 (21·5)	16·70 (15·2)
c42	18·53				542 (19·0)	4·00 (6·3)	22·52 (21·5)
c46	43·19				761 (22·7)	2·63 (15·0)	20·17 (26·6)
c47	3·43				486 (18·7)	2·26 (7·4)	11·36 (20·3)
c49	14·56				576 (16·8)	2·65 (9·3)	14·77 (11·7)
c50	9·45				662 (18·1)	4·24 (5·0)	28·67 (22·8)
Average					591	2·97	17·72
Minimum					471	2·11	11·36
Maximum					761	5·04	31·49

year^{-1}, respectively. The coefficient of variation ranged from 5·0 to 27·8% and from 11·5 to 36·1% for the concentration and flux of DOC respectively (Table II).

Inter-catchment coefficients of variation (Table I) are generally greater than intra-catchment coefficients of variation (Table II), suggesting that the hydrogeologic controls on DOC fluxes are more significant than climatological controls.

Wetland characteristics

Manually derived estimates of the extents of cryptic wetlands indicated that these areas ranged from <0·1 to about 12% of the catchment areas (Table III). The distribution of these cryptic wetlands varied from being small areas that appeared to be hydrologically disconnected from the dominant surface hydrological pathways within the catchments (e.g. c35 and c47), to larger areas, both in upland and lowland areas, that appeared to be hydrologically connected to the dominant surface hydrological pathways (e.g. c37, c42, c50) (Figure 2). In most cases, the cryptic wetlands were not directly connected to the catchment outflow, indicating that if they are the source of DOC, then the DOC is subsequently transported via surface hydrological pathways to the stream.

The manual derivation of the extent of the cryptic wetlands was not a trivial exercise. It took a multiple-person field crew several weeks to search for and then map the wetlands within 230 ha, a small percentage of the 1050 ha (10·5 km^2) watershed. To be able to generalize this study to the rest of the TLW and to other forest regions, an automated method for delineating wetlands was needed.

Wetlands often occur in topographic depressions and/or on flat slopes, and so digital terrain analysis on a DEM was conducted to demarcate these topographic features and the extent of these topographic features was compared with wetlands derived by the manual method.

The DEM used in this study was generated from airborne laser mapping technology. This technology is capable of generating digital elevation data with a precision and accuracy equivalent to traditional ground surveys in a fraction of the time, but at a comparable expense. Airborne laser mapping integrates three systems into a single instrument that is mounted on an airplane: a LiDAR system, an inertial reference system (INS), and a GPS. LiDAR measures the distance to the ground by recording the time it takes a laser pulse to reflect back to the aircraft from the ground; the elapsed time is converted to a distance using knowledge of the speed of light. Unlike aerial photography or satellite imagery, LiDAR can simultaneously map the distance to the tree canopy as well as to the ground beneath the tree canopy, and thus allows for DEMs of the ground

Table III. Wetlands, derived manually using a GPS and automatically using a GIS (based on topographic depressions and slopes $\leq 1·5°$), expressed as an area (m^2) and as a percentage of the catchment area within each of the experimental catchments. For the manually derived wetlands, morphometric indices were defined to estimate the potential for hydrologic flushing of DOC from the slopes surrounding the wetland (dim, ranging from low flushing potential (convex) to high flushing potential (concave)), and the potential for hydrologic efficiency in exporting DOC to surface waters

Catchment	Manually derived wetlands		Automatically derived wetlands		Morphometric indices for manually derived wetlands	
	(m^2)	(%)	(m^2)	(%)	Hydrologic flushing index (dim)	Hydrologic efficiency index (%)
c31	1800	3·33	1150	2·12	0·15	2·49
c32	250	0·39	431	0·67	−0·64	0·39
c33	475	0·20	1269	0·54	0·12	0·15
c34	6925	1·01	6063	0·88	0·00	0·84
c35	25	0·08	81	0·26	0·00	0·08
c37	18 775	12·24	14 306	9·33	0·65	10·05
c39	3388	2·04	7238	4·37	−0·02	1·37
c42	12 125	6·55	12 050	6·51	0·03	5·95
c46	5600	1·30	4875	1·13	0·04	0·99
c47	25	0·07	75	0·22	0·08	0·07
c49	2788	1·92	4044	2·78	0·52	1·22
c50	7325	7·76	7175	7·60	0·03	6·60
Total area	59 501		58 756			

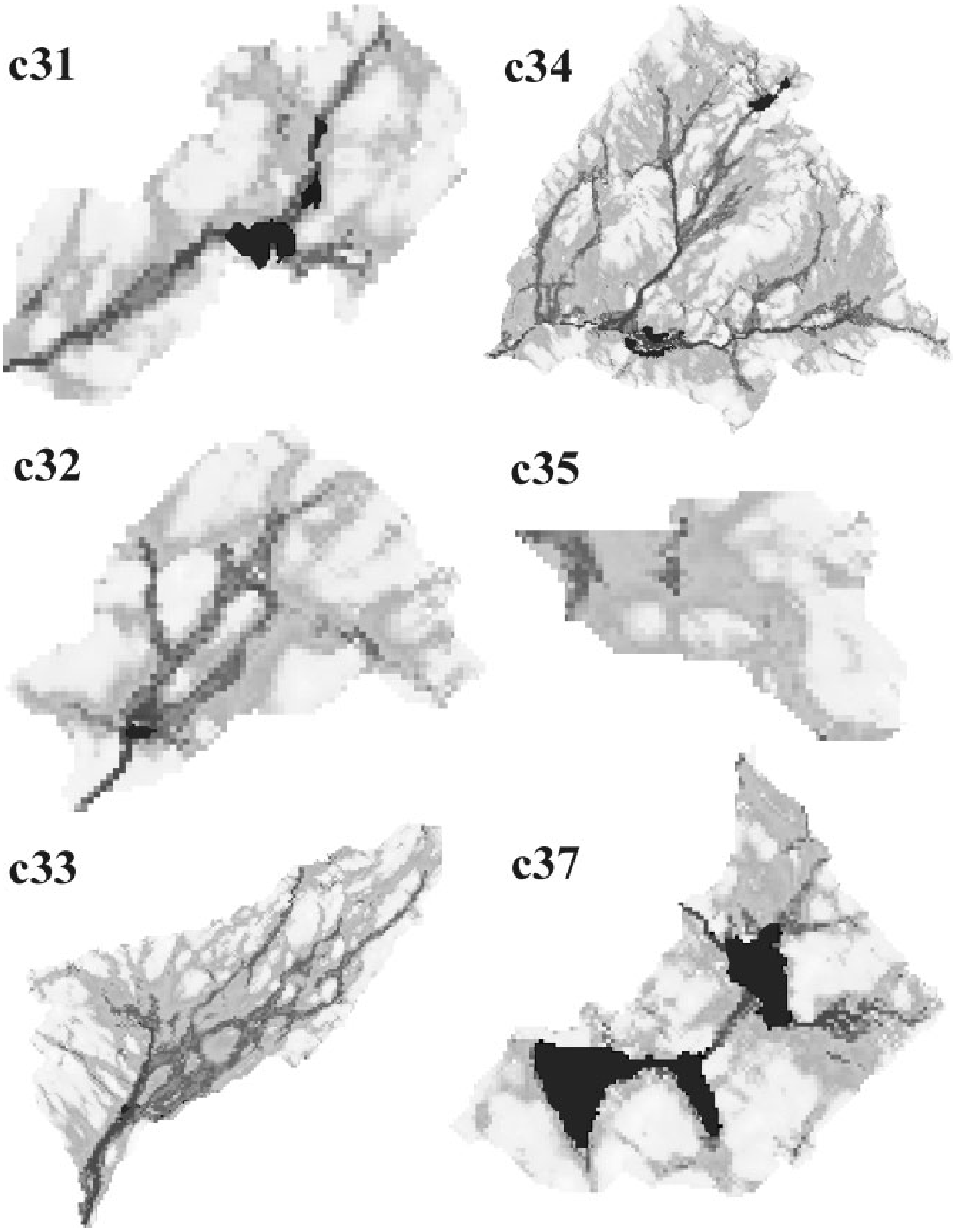

Figure 2. Distribution of the manually derived wetlands (black areas) within each of the experimental catchments. The manually derived wetlands are draped over maps of the topographic index (Beven and Kirkby, 1979), which provides an indication of topographically controlled wetness within each catchment. Small topographic index values (i.e. relatively dry) are indicated by light grey areas and large topographic index values (i.e. relatively wet) are indicated by dark grey areas

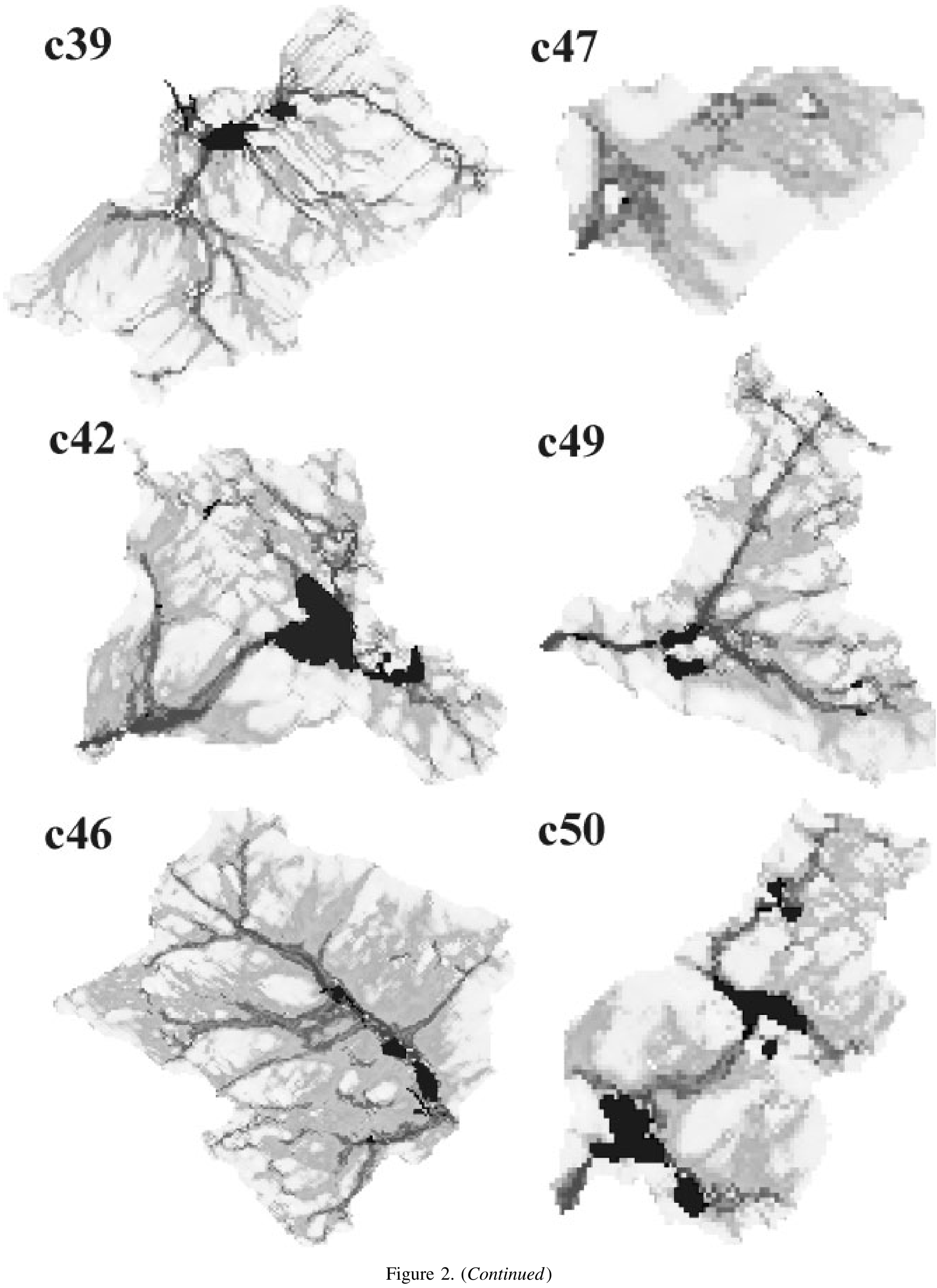

Figure 2. (*Continued*)

surface to be generated. The INS records the roll, pitch, and direction of the aircraft. The GPS records the geographic coordinates of the aircraft (Anonymous, 2002). By integrating these three systems, a DEM was generated with an absolute vertical accuracy of 15 cm and a horizontal accuracy, a function of the operating parameters, of 2·5 m.

Using the 2·5 m LiDAR DEM, topographic depressions and flat slopes were demarcated. The critical threshold for flat slopes was established through an iterative process, where the threshold was increased from 0° to larger slopes until the total area of the combined topographic depressions and flat slopes was approximately equal to the total area of the manually derived wetlands within the catchments (Figure 3). With a critical threshold of less than or equal to 1·5°, the areas of the automatically and manually derived wetlands were similar, with the total areas at 59 501 m^2 and 58 756 m^2 respectively (Table III).

To compare the automatically versus manually derived wetlands within the catchments, both aspatial and spatial statistical analyses were performed. The aspatial correlation of automatically versus manually derived wetlands (%) was significant and strong (Figure 4, $r^2 = 0{\cdot}92$, $p < 0{\cdot}001$). The spatial coincidence of automatically versus manually derived wetlands was variable. Direct coincidence ranged from 0 (no spatial coincidence) to about 60% (Table IV). Catchments with small wetlands in steep and/or convex topography appeared to have lower direct coincidences (e.g. c35 and c42) than catchments with larger wetlands in more gentle and/or concave topography (e.g. c37, c42, c50), reflecting the dependency of the direct coincidence on the magnitude and distribution of the wetlands. The fuzzy coincidence within 100 m of the manually derived wetlands ranged from 14 to 99%, with all but one catchment having a fuzzy coincidence >40% (Figure 4).

To generalize the automated method for deriving wetlands, several data quantity and quality issues needed to be considered. The first issue is that a degradation of the DEM may be required to meet data storage and processing capabilities of the computer. To examine the effects of degrading the 2·5 m LiDAR DEM, the correlation and coincidence of the automatically and manually derived wetlands were computed for 5, 10, 25, 50 and 100 m LiDAR DEMs (Tables IV and V). As the LiDAR DEM was degraded, it was somewhat surprising to see that the relationship of automatically versus manually derived wetlands was relatively stable, with r^2 values remaining relatively constant at grid resolutions less than or equal to 25 m, showing a marginal drop at 50 m, and showing a major drop but remaining significant at 100 m. As the LiDAR DEM was coarsened, the coincidence of automatically and manually derived wetlands generally decreased (Table IV). In general, both direct and fuzzy coincidences decreased slowly up to 10 m grid resolutions, and more precipitously thereafter as the grids were further coarsened.

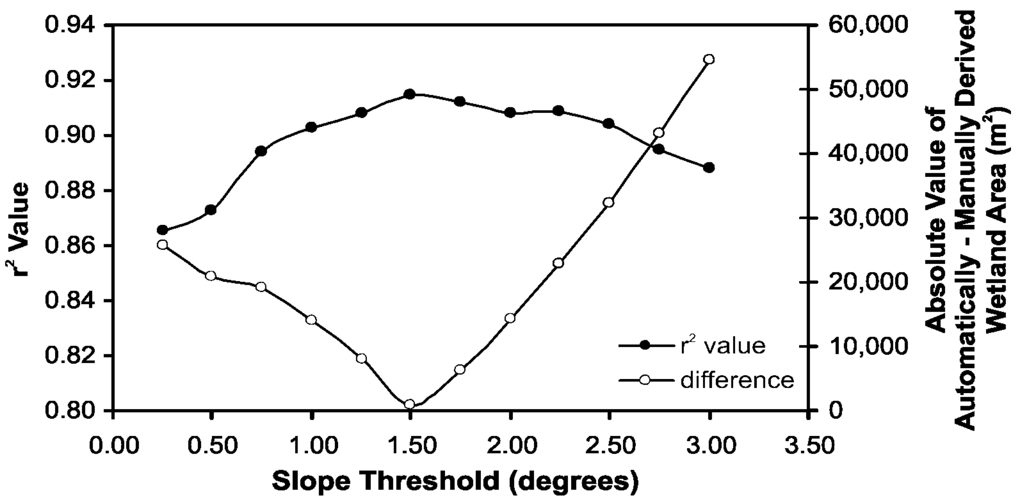

Figure 3. The strength of the relationship (r^2) and absolute value of the difference of automatically and manually derived wetland areas (m^2) for various slope thresholds applied to the 2·5 m LiDAR DEM

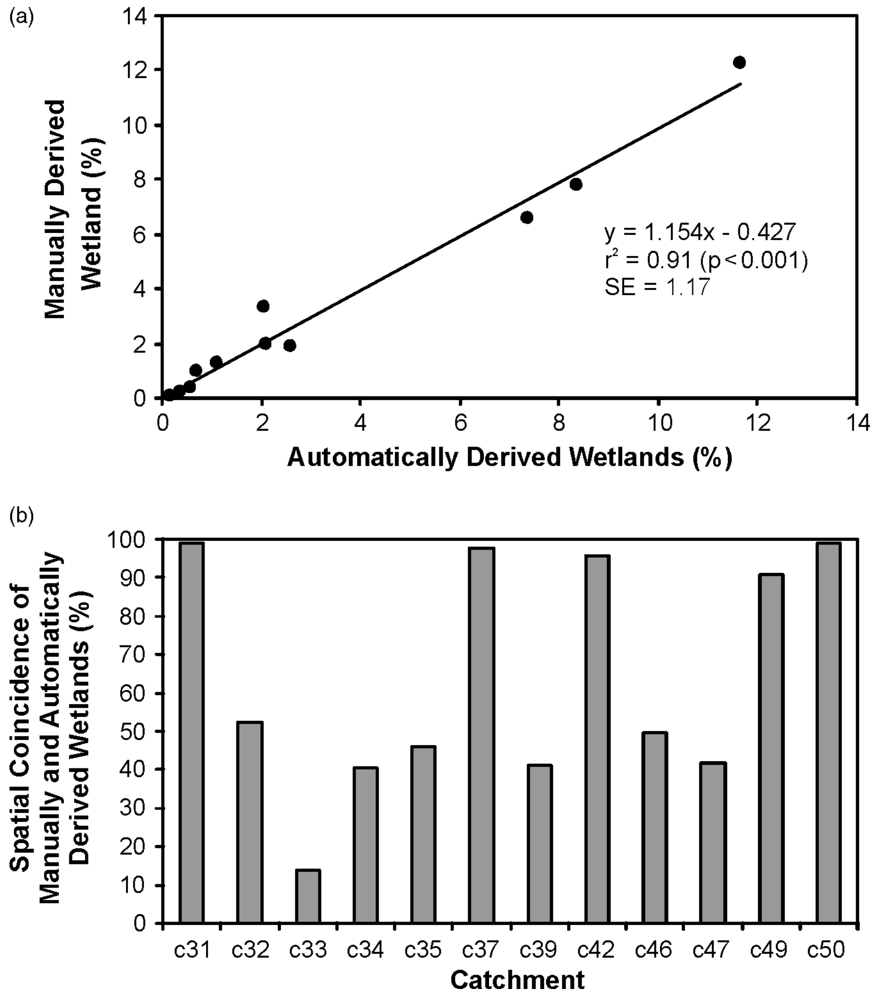

Figure 4. Assessment of accuracy of automatically derived wetlands from the 2·5 m LiDAR DEM: (a) aspatial correlation of automatically versus manually derived wetlands; (b) spatial coincidence of automatically with manually derived wetlands based on membership in and within 100 m of the boundaries of the manually derived wetlands

The second issue is that a LiDAR DEM may not be generally available, and a routinely available DEM may need to be used. Although cryptic wetlands were successfully delineated using terrain analysis on the LiDAR DEM, the airborne laser mapping technology used to generate the LiDAR DEM is an emerging technology that remains expensive and thus not accessible to most researchers. To examine the effects of different sources of DEM, the correlation and coincidence of automatically versus manually derived wetlands were computed for 5·0 m interpolations of the more commonly available DEMs. These included a DEM created specifically for the TLW at 1 : 12 000 and DEMs that were generated through the interpolation of digital contour data acquired from government agencies, including digital contours from the OBM Series (1 : 20 000) and the NTS (1 : 50 000) (Table VI). As previously noted, the correlation between automatically derived wetlands using the 5·0 m LiDAR DEM and the manually derived wetlands shows an $r^2 = 0.98$ ($p < 0.001$).

For the other sources of DEMs, a combination of topographic depressions and varying slope thresholds were used to define the wetlands; the slope threshold increased from 1·5° for the LiDAR DEM, to 1·75° for the TLW DEM and the OBM DEM, and to 2·0° for the NTS DEM (Table VI).

Table IV. Effect of the *scale* of the LiDAR DEM on the spatial coincidence of automatically and manually derived wetlands (the 5 m LiDAR DEM is included in the analyses presented in Table VII). Estimates of both direct and fuzzy coincidence of automatically derived wetlands within a boundary of up to 100 m of the manually derived wetlands (0 to 100%) were calculated

DEM source	Method	Spatial coincidence (%)											
		c31	c32	c33	c34	c35	c37	c39	c42	c46	c47	c49	c50
LiDAR	Direct	36	7	0	8	0	60	14	43	20	0	15	55
2·5 m	Fuzzy	99	52	14	41	46	98	41	96	50	42	91	99
LiDAR	Direct	33	13	6	11	0	65	27	51	25	0	21	52
5 m	Fuzzy	100	53	6	46	0	99	69	96	51	50	92	99
LiDAR	Direct	33	0	0	0	0	62	24	43	24	0	15	40
10 m	Fuzzy	100	100	0	41	0	99	62	92	51	0	36	98
LiDAR	Direct	33	0	0	8	0	51	13	29	23	0	5	27
25 m	Fuzzy	100	0	0	23	0	98	33	85	41	0	29	97
LiDAR	Direct	0	0	0	0	0	53	0	33	10	0	20	7
50 m	Fuzzy	0	0	0	0	0	87	0	56	30	0	40	64
LiDAR	Direct	0	0	0	0	0	0	33	10	0	0	0	25
100 m	Fuzzy	0	0	0	0	0	0	33	40	0	0	0	50

Table V. Effect of the *scale* of the LiDAR DEM on the strength (r^2), significance (p), and standard error of estimate (SE) of the relationship of automatically derived wetlands (%) versus manually derived wetlands (%) (the 5 m LiDAR DEM is included in the analyses presented in Table VI). The different scales were derived by assigning the coarser grid the elevation of the centre of the square of 2·5 m grids

DEM scale (m)	Slope threshold applied (deg)	Automatically versus manually derived wetlands (%)			Automatically derived wetlands (m^2)
		r^2 (p)	SE	Equation	
2·5	1·5	0·91 ($p < 0{\cdot}001$)	1·172	$y = 1{\cdot}154x - 0{\cdot}427$	58 756
5	1·5	0·98 ($p < 0{\cdot}001$)	0·598	$y = 0{\cdot}982x + 0{\cdot}021$	58 775
10	1·5	0·97 ($p < 0{\cdot}001$)	0·671	$y = 0{\cdot}998x + 0{\cdot}038$	57 500
25	1·5	0·99 ($p < 0{\cdot}001$)	0·323	$y = 0{\cdot}825x + 0{\cdot}313$	61 875
50	1·5	0·88 ($p < 0{\cdot}001$)	1·378	$y = 0{\cdot}993x - 0{\cdot}013$	57 500
100	1·5	0·36 ($p < 0{\cdot}05$)	3·211	$y = 0{\cdot}352x + 1{\cdot}664$	50 000

Based on the criteria of the strength, significance, and standard error of estimate of the relationship of automatically versus manually derived wetlands, after the LiDAR DEM, the next best DEM for automatically defining wetlands was the OBM, then the NTS, and finally the TLW (which was made specifically for the TLW research program). The relationship of automatically versus manually derived wetlands was $r^2 = 0{\cdot}63$ ($p < 0{\cdot}01$, SE $= 2{\cdot}443$) and $r^2 = 0{\cdot}58$ ($p < 0{\cdot}01$, SE $= 2{\cdot}615$), for the OBM and NTS DEMs respectively (Table VI). No systematic effect of source was observed on the slope of the relationships, as the presence of outliers dominated the relationships. For example, the removal of the single outlier in the relationship based on the OBM DEM improved the regression's strength ($r^2 = 0{\cdot}92$), significance ($p < 0{\cdot}001$), and standard error of estimate (SE $= 1{\cdot}115$), and increased the slope from 0·691 to 0·785, closer to the desired 1·000 slope. Generally, large wetlands were underestimated and small wetlands were overestimated, resulting in instabilities in the relationships.

Based on the criteria of the coincidence of automatically with manually derived wetlands, after the LiDAR DEM, the next best DEM for automatically defining wetlands was the OBM and NTS. However, the

Table VI. Effect of the *source* of the DEM on the strength (r^2), significance (p), and standard error of estimate (SE) of the relationship of automatically derived wetlands (%) versus manually derived wetlands (%). The different sources were LiDAR data and aerial photography collected from various agencies, including the TLW research program, the provincial government (OBM) and the federal government (NTS)

DEM scale (m)	Slope threshold applied (deg)	Automatically versus manually derived wetlands (%)			Automatically derived wetlands (m^2)
		r^2 (p)	SE	Equation	
LiDAR	1·5	0·98 ($p < 0{\cdot}001$)	0·598	$y = 0{\cdot}982x + 0{\cdot}021$	58 775
TLW (1 : 12 000)[a]	1·75	0·44 ($p < 0{\cdot}05$)	3·005	$y = 0{\cdot}598x + 1{\cdot}186$	61 650
OBM (1 : 20 000)[b]	1·75	0·63 ($p < 0{\cdot}01$)	2·443	$y = 0{\cdot}691x + 0{\cdot}885$	56 700
NTS (1 : 50 000)[c]	2·0	0·58 ($p < 0{\cdot}01$)	2·615	$y = 1{\cdot}804x - 1{\cdot}604$	60 575

[a] Interpolated from 1 : 16 500 aerial photography.
[b] Interpolated from 1 : 50 000 aerial photography.
[c] Interpolated from 1 : 65 000 to 1 : 85 000 aerial photography.

Table VII. Effect of the *source* of the DEM on the spatial coincidence of automatically and manually derived wetlands. Estimates of both direct and fuzzy coincidence of automatically derived wetlands within a boundary of up to 100 m of the manually derived wetlands (0 to 100%) were calculated

DEM source	Method	Spatial coincidence (%)											
		c31	c32	c33	c34	c35	c37	c39	c42	c46	c47	c49	c50
LiDAR	Direct	33	13	6	11	0	65	27	51	25	0	21	52
	Fuzzy	100	53	6	46	0	99	69	96	51	50	92	99
TLW	Direct	22	0	0	1	0	23	0	39	25	0	9	4
	Fuzzy	100	0	0	8	0	86	0	92	36	100	68	46
OBM	Direct	0	17	0	0	0	44	0	19	10	0	2	0
	Fuzzy	100	67	0	32	68	93	0	95	62	0	57	94
NTS	Direct	6	3	0	0	0	26	1	5	2	0	1	3
	Fuzzy	98	77	8	29	95	94	26	93	34	67	66	85

coincidence decreased significantly when switching from the 5 m LiDAR DEM to the other sources of DEMs (Table VII).

These research findings underscore the influence of the scale and the source of the DEM on wetland studies. DEMs that are based on the elevation of the ground surface (e.g. LiDAR), rather than the canopy surface (e.g. TLW, OBM, NTS), will produce more accurate estimates of wetlands, even if the DEM resolution is significantly degraded.

Role of wetlands in DOC export

There was substantial natural variation in the average concentration of DOC (ranging from 2·11 to 5·04 mgC l^{-1} year^{-1}) and flux of DOC (ranging from 11·36 to 31·49 kgC ha^{-1} year^{-1}) among the experimental catchments. In previous studies, significant relationships between the proportion of wetlands contributing to surface waters and the concentration and flux of DOC in surface waters have been observed (e.g. Mulholland and Kuenzler, 1979; Urban *et al*., 1989; Eckhardt and Moore, 1990; Hemond, 1990; Koprivnjak and Moore, 1992; Hope *et al*., 1994; Dillon and Molot, 1997). In this study, wetlands with open canopy and/or canopy with distinct canopy species were not observed, but cryptic wetlands, which ranged from <0·1 to 12% of the area of the catchments, were observed. Despite the relatively small size of the cryptic wetlands, there was a significant correlation between the proportion of cryptic wetlands within catchments (%) and the average DOC export (kgC ha^{-1} $year^{-1}$) (Tables VIII and IX).

The relationships for the manually and automatically derived wetlands were (Figures 5 and 6):

$$\text{DOC (kgC ha}^{-1}\text{ year}^{-1}) = 1{\cdot}627 \times \text{Manually Derived Cryptic Wetlands (\%)} + 12{\cdot}717$$
$$(r^2 = 0{\cdot}88,\ p < 0{\cdot}001)$$
$$\text{DOC (kgC ha}^{-1}\text{ year}^{-1}) = 1{\cdot}932 \times \text{Automatically Derived Cryptic Wetlands (\%)} + 11{\cdot}856$$
$$(r^2 = 0{\cdot}85,\ p < 0{\cdot}001)$$

In these relationships, the y-intercept indicates contributions to DOC export from non-cryptic wetland areas of about 12kgC ha^{-1} $year^{-1}$, and the slope indicates contributions to DOC export from cryptic wetlands that increase export from the baseline of about 12kgC ha^{-1} $year^{-1}$ to 32 kgC ha^{-1} $year^{-1}$ (Figures 5 and 6). There was no significant difference in either the y-intercept ($p = 0{\cdot}557$) or the slope ($p = 0{\cdot}354$) between the two relationships, providing support for the use of digital terrain analyses for delineating wetlands for the purpose of modelling the export of DOC.

Further digital terrain analyses of the morphologic properties of the cryptic wetlands were conducted in an attempt to improve the explanation of variance in the average annual export of DOC. One morphometric index evaluated the potential for hydrologic flushing of DOC from soils in the slopes surrounding the cryptic wetlands. Hydrologic flushing of DOC is regulated by water table fluctuations. When the water table is low

Table VIII. Effect of the *scale* of the DEM on the strength (r^2), significance (p), and standard error of estimate (SE) of the relationship of automatically derived wetlands (%) versus DOC export (kgC ha^{-1} $year^{-1}$)

DEM scale (m)	Slope threshold applied (deg)	Automatically derived wetlands (%) versus DOC (kgC ha^{-1} $year^{-1}$)		
		r^2 (p)	SE	Equation
2·5	1·5	0·85 ($p < 0{\cdot}001$)	2·714	$y = 1{\cdot}933x + 11{\cdot}856$
5	1·5	0·88 ($p < 0{\cdot}001$)	2·384	$y = 1{\cdot}622x + 12{\cdot}675$
10	1·5	0·88 ($p < 0{\cdot}001$)	2·433	$y = 1{\cdot}649x + 12{\cdot}701$
25	1·5	0·84 ($p < 0{\cdot}001$)	2·755	$y = 1{\cdot}322x + 13{\cdot}296$
50	1·5	0·73 ($p < 0{\cdot}001$)	3·615	$y = 1{\cdot}571x + 12{\cdot}833$
100	1·5	0·30 ($p = 0{\cdot}064$)	5·835	$y = 0{\cdot}560x + 15{\cdot}477$

Table IX. Effect of the *source* of the DEM on the strength (r^2), significance (p), and standard error of estimate (SE) of the relationship of automatically derived wetlands (%) versus DOC export (kgC ha^{-1} $year^{-1}$)

DEM source	Slope threshold applied (deg)	Automatically derived wetlands (%) versus DOC (kgC ha^{-1} $year^{-1}$)		
		r^2 (p)	SE	Equation
LiDAR	1·5	0·85 ($p < 0{\cdot}001$)	2·714	$y = 1{\cdot}933x + 11{\cdot}856$
TLW (1 : 12 000)[a]	1·75	0·31 ($p = 0{\cdot}06$)	5·815	$y = 0{\cdot}866x + 14{\cdot}982$
OBM (1 : 20 000)[b]	1·75	0·42 ($p < 0{\cdot}05$)	5·319	$y = 0{\cdot}980x + 14{\cdot}612$
NTS (1 : 50 000)[c]	2·0	0·39 ($p < 0{\cdot}05$)	5·444	$y = 2{\cdot}639x + 14{\cdot}525$

[a] Interpolated from 1 : 16 500 aerial photography.
[b] Interpolated from 1 : 50 000 aerial photography.
[c] Interpolated from 1 : 65 000 to 1 : 85 000 aerial photography.

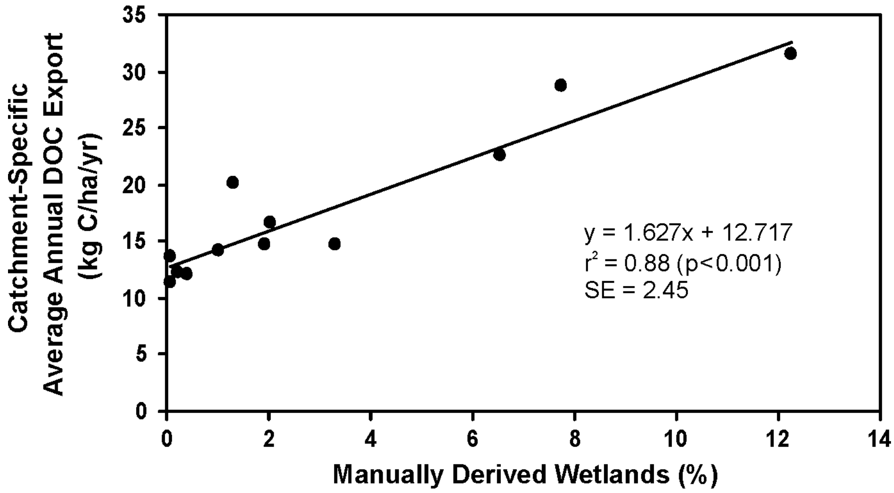

Figure 5. Relationship of manually derived wetlands versus the average annual export of DOC

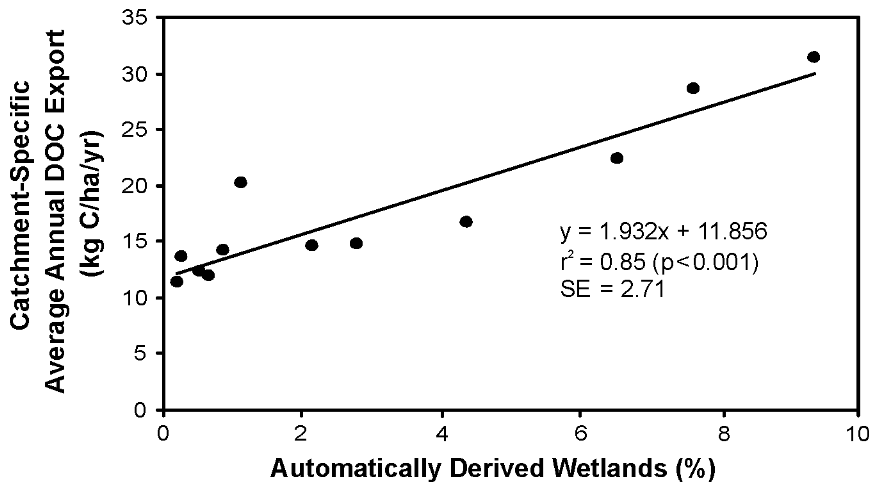

Figure 6. Relationship of automatically derived wetlands versus the average annual export of DOC

there is an accumulation of nutrients within the soil profile, resulting in low DOC export to adjacent waters. As the water table rises it flushes the soil profile, and DOC in the soil profile is available for export. As the water table reaches the soil surface it flushes the DOC-rich portion of the soil profile, resulting in high DOC export to surface waters (Hornberger *et al.*, 1994; Creed *et al.*, 1996). We hypothesized that cryptic wetlands vary in their potential for hydrologically flushing the soils in the slopes surrounding the cryptic wetland. For example, if a cryptic wetland is located in a topographic depression or flat area where the surrounding hillslopes are relatively steep, then any increase in the water table will cause only minimal increases in the area of the cryptic wetland. If, on the other hand, cryptic wetlands are located in a topographic depression or flat area where the surrounding hillslopes are relatively gentle, then any increase in the water table will cause larger changes in the area of the cryptic wetland (Creed and Band, 1998). An index representing the hydrologic flushing potential of the cryptic wetlands was estimated through calculation of the profile curvature of the slopes draining into the cryptic wetlands; if more than one cryptic wetland was found in any catchment, then the hydrologic flushing index was based on an average weighted by the original areas of the cryptic wetlands.

Inclusion of the hydrologic flushing index did not improve the explanation of variance in the regression model, suggesting that the surrounding slopes, be they steep or gentle, are not significant in terms of contributing to DOC export (Table III; the relationship of hydrologic flushing index versus DOC export (kgC ha^{-1} $year^{-1}$) was not significant ($r^2 = 0{\cdot}19,\ p = 0{\cdot}154$)).

Another morphometric index evaluated the percentage of cryptic wetlands that were connected via surface hydrologic pathways to the stream. We hypothesized that cryptic wetlands vary in their hydrologic export efficiency. Cryptic wetlands can occur in topographic depressions and/or flat areas that are isolated from the stream and, therefore, be inefficient in terms of DOC export. Alternatively, cryptic wetlands can be connected to the stream and efficiently transport DOC via surface hydrologic pathways to the stream. Substitution of cryptic wetlands with the index representing the hydrologic efficiency of the cryptic wetlands (i.e. the ratio of connected to total cryptic wetlands) did not improve the explanation of variance in the regression model, suggesting that most cryptic wetlands were connected to surface hydrologic pathways (Table III, $r^2 = 0{\cdot}88$ ($p < 0{\cdot}001$) for both the relationship of cryptic wetland (%) versus DOC export (kgC ha^{-1} $year^{-1}$) and the relationship of the proportion of cryptic wetland connected to surface hydrologic pathways (%) versus DOC export (kgC ha^{-1} $year^{-1}$)).

Although a significant relationship was observed between cryptic wetlands (%) and DOC export (kgC ha^{-1} $year^{-1}$), it was not determined how cryptic wetlands increased DOC export. Mineral soils are estimated to be a major repository of C (i.e. 97% of the soil C pool), with an average C pool of 11 227 000 kg, ranging from 1 890 000 to 41 250 000 kg, depending on the catchment (Morrison, 1985, 1990; Johnson and Lindberg, 1992). In contrast, organic soils, in topographic depressions and flat areas, are estimated to be a minor repository of C (i.e. 3% of the soil C pool), with an average C pool of 555 000 kg, ranging from 3000 to 2 103 000 kg, depending on the catchment. This estimate was calculated by assuming a conservative estimate of an average depth of organic soil (peat) of 2 m, a peat density of 112 kg m^{-3} (Elder *et al.*, 2000), and an organic C fraction in peat of 0·5 (Gorham, 1991).

There are at least two scenarios for how cryptic wetlands increase DOC export. In the first scenario, DOC originates from the major repository of C in soils on slopes contributing to the cryptic wetlands. While DOC in the mineral horizons is strongly adsorbed to aluminium and iron oxides/hydroxides and to clay minerals (Kalbitz *et al.*, 2000), DOC in the forest floor may bypass the mineral horizons via surface or near-surface hydrologic pathways to the cryptic wetland and be conveyed over the surface of the saturated soils in the cryptic wetland to the stream. In the second scenario, DOC originating from the soils on slopes contributing to the cryptic wetlands largely remains in the catchment, and DOC originating from the cryptic wetlands is exported to the stream. In the cryptic wetlands, DOC may be generated by fluctuations in the water table, where microbial products that accumulate during dry conditions are subsequently flushed during wet conditions (Kalbitz *et al.*, 2000). Alternatively, DOC may be generated by a water table near the surface of the cryptic wetland, in which anaerobic decomposition dominates over aerobic decomposition and opportunities arise for the export of the water-soluble intermediate metabolites from the less efficient anaerobic decomposition pathway (Otsuki and Hanya, 1972; Mulholland *et al.*, 1990; Sedell and Dahm, 1990; Kalbitz *et al.*, 2000). Future investigations in the TLW will focus on identifying the mechanisms of DOC export and changes to DOC export resulting from climatic variability.

CONCLUSIONS

Recent research at the TLW has focused on the patterns and processes of DOC export from its experimental catchments. Natural variation in the average annual DOC export among these experimental catchments is significant. Initial steps in the research program were to develop catchment DOC export models so that the major sources of the natural variation in DOC export could be identified. Previous studies have shown that there is a significant relationship between wetlands (with distinctive forest canopies) and DOC export. As the forest canopy is homogeneous in the TLW, this study considered whether wetlands that had no distinctive forest canopy, i.e. wetlands that were hidden under the homogeneous forest canopy, were related to DOC export. For the physiographic region of the TLW, characterized by thin soils on solid geology, both manual and automatic techniques were developed for estimating cryptic wetlands. There was a significant relationship between cryptic wetlands and DOC export. Cryptic wetlands were observed to explain about 90% of the natural variation in the average annual DOC export among the catchments. The inclusion of both cryptic and non-cryptic wetlands in DOC export models is recommended for improved predictions of DOC export, particularly from catchments with comparatively small DOC fluxes.

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