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Variable flushing mechanisms and landscape structure control stream DOC export during snowmelt in a set of nested catchments

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Abstract Stream DOC dynamics during snowmelt have been the focus of much research, and numerous DOC mobilization and delivery mechanisms from riparian and upland areas have been proposed. However, landscape structure controls on DOC export from riparian and upland landscape elements remains poorly understood. We investigated stream and groundwater DOC dynamics across three transects and seven adjacent but diverse catchments with a range of landscape characteristics during snowmelt (April 15–July 15) in the northern Rocky Mountains, Montana. We observed a range of DOC export dynamics across riparian and upland landscape settings and varying degrees of hydrologic connectivity between the stream, riparian, and upland zones. DOC export from riparian zones required a hydrologic connection across the riparian–stream interface, and occurred at landscape positions with a wide range of upslope accumulated area (UAA) and wetness status. In contrast, mobilization of DOC from the uplands appeared restricted to areas with a hydrologic connection across the entire upland–riparian–stream continuum, which generally occurred only at areas with high UAA, and/or at times of high wetness. Further, the relative extent of DOC-rich riparian and wetland zones strongly influenced catchment DOC export. Cumulative stream DOC export was highest from catchments with a large proportion of riparian to upland area, and ranged from 6.3 to 12.4 kg ha^{-1} across the study period. This research suggests that the spatial/temporal intersection of hydrologic connectivity and DOC source areas drives stream DOC export.

Keywords Catchment · DOC · Flushing · Landscape structure · Snowmelt · Stream

Introduction

Stream DOC export from catchments is a significant component of the carbon cycle (Laudon et al. 2004a; Neill et al. 2006; Johnson et al. 2006; Waterloo et al. 2006; Jonsson et al. 2007) and can strongly impact contaminant transport (Imai et al. 2003; Wei et al. 2008). In alpine and subalpine catchments, the majority of annual DOC flux often occurs during snowmelt (Hornberger et al. 1994; Boyer et al. 1997, 2000; Laudon et al. 2004a). The process by which DOC is transported to the stream is commonly referred to as hydrologic nutrient flushing, whereby organic material undergoes a period of accumulation in the soil, and is then released to the stream during snowmelt or precipitation events (Burns 2005). This

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flushing can lead to a characteristic peak in DOC concentrations on the rising limb of the stream hydrograph (Hornberger et al. 1994; Boyer et al. 1997; Inamdar et al. 2004; Hood et al. 2006; Agren et al. 2008; van Vevrseveld et al. 2008). However, the controls on and the variability of DOC flushing at the upland, riparian, and catchment scales are poorly understood (Wieler and McDonnell 2006; van Vevrseveld et al. 2008).

DOC flushing is often used to describe different, but related processes. At baseflow, stream DOC concentrations are generally low due to groundwater inflows through deep, low DOC mineral soil (Fig. 1, Scenario 1) (Hornberger et al. 1994). However, rise of the groundwater table into shallow DOC-rich riparian soil layers at the beginning of snowmelt or precipitation events can lead to a large increase in DOC export from riparian soil to the stream (Fig. 1, Scenario 2) (Bishop et al. 1994; Hornberger et al. 1994; Boyer et al. 1997, 2000; Bishop et al. 2004; Laudon et al. 2004b). This process can be augmented by transmissivity feedback, in which the rising water table enters soils with increasing hydraulic conductivity, leading to increased lateral flow contributions to runoff (Bishop et al. 2004; Laudon et al. 2004b; Wieler and McDonnell 2006). Here, we define this rise of the water table into shallow soils a one-dimensional (1D) process. Often, there is a limited supply of DOC in riparian zones, and persistent 1D flushing can result in decreased DOC concentrations through snowmelt or precipitation events (Hornberger et al. 1994; Boyer et al. 1997).

In addition to 1D flushing, McGlynn and McDonnell (2003) proposed a two-dimensional (2D) nutrient flushing mechanism, which is supported by Bishop et al. (2004) and Hood et al. (2006). In this scenario, catchment DOC export occurs as a function of the connectivity between near-stream and upland areas (Fig. 1, Scenario 3). The initial increase in stream DOC concentrations occurs during the rise of the water table into shallow organic-rich riparian soils. A second source of high DOC on the rising limb of the stream hydrograph occurs as uplands become hydrologically connected to the riparian zones, allowing for quick transmission of upland water that is rich in DOC (Bishop et al. 2004) along preferential flow paths (Fig. 1, Scenario 3a) (McGlynn and McDonnell 2003). This high DOC initial upland runoff is then diluted with lower DOC matrix water (Fig. 1, Scenario 3b), leading to lower stream DOC concentrations on the falling limb of the stream hydrograph (McGlynn and McDonnell 2003). We suggest that in high elevation, snowmelt-dominated catchments, the relative importance of riparian and upland sources of DOC can vary strongly through space and time and is largely dependent upon riparian extent and the degree of hydrologic connectivity between the stream and the riparian and upland zones.

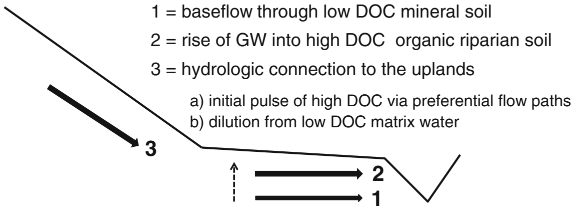


Fig. 1 Conceptual model of DOC export from the soil to the stream. During times of low flow, such as baseflow, groundwater travels through low DOC mineral soil, and stream DOC concentrations are low (Scenario 1). As flow begins to increase during snowmelt or precipitation events, the groundwater table rises into shallow organic-rich riparian soil, and inputs of DOC from the soil to the stream increase (Scenario 2). As the groundwater table continues to rise, a hydrologic connection develops across the upland–riparian–stream continuum (Scenario 3). An initial pulse of high DOC water from the uplands is transmitted along preferential flow paths (3a). Runoff from the uplands is then diluted by low DOC matrix water traveling through mineral soil (3b)

Landscape structure can strongly influence the degree of hydrologic connectivity across the upland–riparian–stream (URS) continuum (Jencso et al. 2009), and therefore DOC export. Following Jencso et al. (2009), we define hydrologic connectivity as the time period when a groundwater connection exists between landscape elements (e.g. stream, riparian, and upland zones). Through a combination of extensive groundwater monitoring (146 recording groundwater wells) and landscape level topographic analysis, Jencso et al. (2009) found that the duration and timing of URS hydrologic connectivity was a function of upslope accumulated area (UAA). They found a strong positive relationship between URS hydrologic connectivity and UAA ($r^2 = 0.91$), with the highest and most persistent URS hydrologic connectivity at landscape positions with large UAA. Here, we seek to investigate the effect of landscape position and hydrologic connectivity on the spatial and temporal variability of stream DOC export during snowmelt in a subalpine catchment in the northern

Rocky Mountains. We analyzed stream and groundwater DOC dynamics during snowmelt (April 15–July 15) across three transects and seven diverse but adjacent catchments to address the following questions:

1. What are the dominant DOC source areas during snowmelt?
2. How does the spatial extent and frequency of DOC source areas impact DOC export at the catchment scale?

Site description

The study site was the upper Tenderfoot Creek Catchment (2,280 ha), located within the U.S. Forest Service (USFS) Tenderfoot Creek Experimental Forest (TCEF) (lat. 46°55′ N., long. 110°52′ W.) in the Little Belt Mountains of central Montana (Fig. 2). Tenderfoot Creek drains into the Smith River, a tributary of the Missouri River. Elevation ranges from 1,840 to 2,421 m, with a mean of 2,205 m. Mean annual precipitation is 880 mm, with ~70% falling as snow from November through May (Farnes et al. 1995). Monthly precipitation peaks in December or January (100–120 mm per month), and declines to 45–55 mm per month from July through October. Tenderfoot Creek runoff averages 250 mm per year, with peak flows typically in late May or early June. Mean annual temperature is 0°C, and mean daily temperatures range from −8.4°C in December to 12.8°C in July (Farnes et al. 1995).

The geology is characterized by granite gneiss, shale, quartz porphyry, and quartzite (Farnes et al. 1995). In the uplands, the major soil group is loamy skeletal, mixed Typic Cryochrepts, while the riparian zones are composed of mixed Aquic Cryoboralfs (Holdorf 1981). Soil depths range from 0.5 to 1 m in the uplands, and 1 to 2.0 m in the riparian zones (Jencso et al. 2009).

Riparian vegetation is dominated by sedges (*Carex* spp.) and rushes (Juncaceae spp.) in the headwaters, where riparian soil is high in organic matter and fine silt and clay textured, and water tables are at or near the soil surface (Jencso et al. 2009). In riparian areas with deeper water tables and coarsely textured soils, Willows (*Salix* spp.) are often present. In the uplands, Lodgepole pine (*Pinus contorta*) is the dominant overstory vegetation (Farnes et al. 1995), and Grouse whortleberry (*Vaccinium scoparium*) primarily composes the understory vegetation (Mincemoyer and Birdsall 2006).

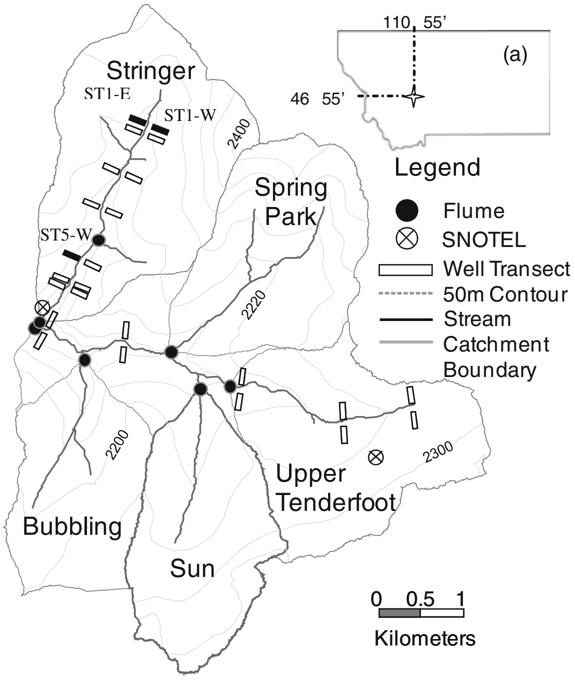


Fig. 2 Location of the Tenderfoot Creek Experimental Forest (TCEF), with delineations of the sub-catchments, and locations of the flumes (at the outlet of each sub-catchment) and the Lower Stringer Creek SNOTEL site. Transect locations are denoted by *rectangles*, and the three utilized for this study within the Stringer Creek Watershed are shown in *black*

There are seven adjacent and partially nested, gauged sub-catchments in the TCEF (Table 2). In general, the catchments have gentler slopes near the headwaters, with steeper slopes near the catchment outlets. Middle Stringer Creek (MSC) and Lower Stringer Creek (LSC) have an intermediate extent of riparian and wetland area, Sun Creek (SC) has large seeps and wetland areas at the headwaters, Bubbling Creek (BC) has less extensive riparian and wetland areas, Spring Park Creek (SPC) has an extensive riparian and wetland area in the middle of the catchment, and Upper Tenderfoot Creek (UTC) has a large network of wetlands at the headwaters. Lower Tenderfoot Creek (LTC) is the largest catchment that encompasses these sub-catchments. The Stringer Creek Catchment (Middle and Lower) was utilized for more intensive data collection and divided into three sub-catchments for data analysis. These sub-catchments were the headwaters to Transect 1 (HW–ST1), Transect 1 to MSC (T1–MSC), and MSC to LSC (MSC-LSC).

Methods

Terrain analysis

An ALSM (airborne laser swath mapping, commonly known as LIDAR, courtesy of the National Center for Airborne Laser Mapping—NCALM) derived 10 m digital elevation model (DEM) was used to calculate UAA (amount of land area draining to a particular location, calculated for the toeslope well position at the transition from upland to riparian zone) and slope (average slope along the fall line from the highest upland location to the toeslope along each transect). UAA was calculated using a triangular multiple flow-direction algorithm following the methods of Seibert and McGlynn (2007) and Jencso et al. (2009). Riparian zone width was mapped with a GPS survey (Trimble GPS 5700 receiver—accurate to within 1–5 cm) and corroborated with ALSM-derived 3 m DEM analysis (Jencso et al. 2009). The riparian–upland boundary was determined in the field, based upon break in slope and change in soil characteristics (depth, gleying, organic matter accumulation, texture) (McGlynn and Seibert 2003; Seibert and McGlynn 2007; Pacific et al. 2008; Jencso et al. 2009). See Jencso et al. (2009) for a more detailed description of terrain analyses in the TCEF. We calculated the percentage of time that URS hydrologic connectivity existed by dividing the total number of days that a groundwater table was present along the URS continuum by the total snowmelt period (91 days) (Jencso et al. 2009). For this study, we define the snowmelt period as April 15–July 15, 2007, which encompassed pre-snowmelt, snowmelt, and the recession to baseflow ($\sim$0.01 mm h^{-1}) (Fig. 3).

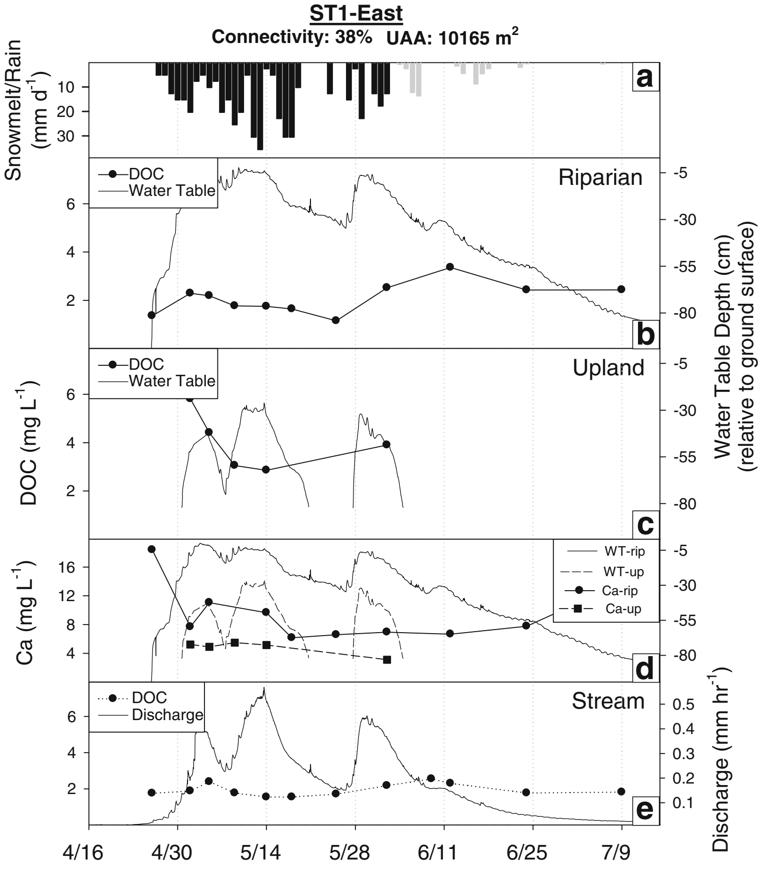


Fig. 3 **a** Soil water inputs from snowmelt (*black bars*) and precipitation (*grey bars*), **b** ST1-E riparian well, **c** ST1-E upland well, **d** riparian and upland groundwater height and Ca concentrations, and **e** stream DOC concentrations and discharge from April 15 to July 15, 2007. The percentage of the study period that upland–riparian–stream connectivity existed, and upslope accumulated area (UAA) at the riparian measurement location are listed at the *top of the figure*. Stream discharge is from the Lower Stringer Creek Flume

Measurement locations

This research was conducted concurrently with other research objectives and included locations and instrumentation both universal and specific to this study (Pacific et al. 2008, 2009; Riveros-Iregui et al. 2008, in review; Riveros-Iregui and McGlynn 2009; Jencso et al. 2009). Measurements were collected at the outlets of each of the sub-catchments within the TCEF (MSC, LSC, SPC, BC, SC, UTC, and LTC), as well as at Onion Park (headwaters of Tenderfoot Creek). In addition, 14 transects were installed by Jencso et al. (2009) in the Stringer Creek Catchment, and eight in the Tenderfoot Creek Catchment (Fig. 2). Three transects within the Stringer Creek Catchment were utilized for intensive monitoring in this study because they represented the range of landscape settings and hydrologic dynamics observed at TCEF. The Stringer Creek transects were located in seven pairs, with each pair consisting of one transect on both the east (E) and west (W) side of Stringer Creek, which flows from the north to the south. The transects are numbered sequentially from upstream to downstream, followed by an E or W, designating the east or west side of Stringer Creek. On each transect, one measurement location was installed in both the riparian and upland zones. For this study, measurements were collected on ST1-E and ST1-W (most upstream transects, at the headwaters of the Stringer Creek), and ST5-W (just below the middle of the catchment). Detailed topographic maps of these transects are presented in Fig. 5r and s in Jencso et al. (2009).

Hydrometric monitoring

Groundwater levels were recorded at the riparian and upland well on each of the focus transects along Stringer Creek. The riparian well was located near the toe-slope (the transition point between the riparian and upland zone), and the upland well was located on the lower hillslope (1–5 m above the break in slope). The wells consisted of 3.8 cm (1.5 inch) inside-diameter PVC, screened across the completion depth (to bedrock) to 10 cm below the ground surface. Completion depths ranged from 0.5 to 1 m in the uplands and 1 to 1.5 m in the riparian zones. Groundwater levels were recorded every 60 min with water level capacitance rods (Trutrack, Inc., ±1 mm resolution). Capacitance rod measurements were corroborated with manual weekly measurements using an electric water level tape.

Stream discharge was measured at flumes at the outlet of each of the seven catchments. Stage at each flume was recorded at 15 min intervals with float potentiometers (installed and maintained by the USFS) and water level capacitance rods recording at hourly intervals (Trutrack, Inc., ±1 mm resolution). Stage was also measured at the outlet of Onion Park, at the headwaters of Tenderfoot Creek. However, discharge could not be calculated as no flume was installed. Hourly measurements of snow water equivalent (SWE) were obtained from two Natural Resource Conservation Service snow survey telemetry (SNOTEL) stations located in TCEF, one at Onion Park (2,259 m, within 2 km and at approximately the same elevation as the headwaters of Stringer Creek), and one at LSC (1,996 m).

Water sampling

Water samples for DOC analysis were collected in 250 ml HDPE bottles. Samples were collected approximately every 2–4 days from the flumes during high flows (beginning of May through the beginning of June) as well as from the outlet of Onion Park, which flows into the headwaters of Tenderfoot Creek. Weekly samples were collected for the weeks before and after this time period. Water samples were collected from wells (when water was present) along each transect every 3–7 days, and wells were purged until dry the day before sampling occurred. The water samples were passed through a 0.45 μm filter into 30 ml amber high density polyethylene (HDPE) bottles within 1–12 h of collection (dependent upon location and time of sampling). Each sample was acidified to pH 1–2 with 6 N HCl, kept in a cooler during transport to Montana State University (MSU), and then frozen at −20°C until analysis.

DOC analysis

Total DOC was analyzed with a high-temperature combustion technique at the MSU Watershed Hydrology Analytical Facility using a Shimadzu TOC-V C-analyzer (Shimadzu Corp., Kyoto, Japan). The instrument was calibrated at the beginning of every run with 3–5 standards ranging from 0.10 to 10.0 mg C l^{-1} (prepared from reagent grade potassium hydrogen phthalate). Method detection limits were 0.1 mg l^{-1}, and analytical precision was within 0.05 mg l^{-1}.

Solute analysis

We collected water samples for calcium (Ca) analysis to help trace the movement of upland water into riparian zones (Covino and McGlynn 2007) and provide corroborating evidence for interpretation of riparian and upland DOC dynamics. In the TCEF, pre-snowmelt upland groundwater Ca concentrations were ~5 mg l^{-1} and consistent across snowmelt, while riparian Ca concentrations were 10–20 mg l^{-1}. Therefore, riparian Ca dilution by lower Ca upland water could be used to infer source water mixing (Jencso et al., in review). Water samples were collected in 250-ml HDPE bottles, filtered through a 0.45-mm PTFE membrane filter, then stored at 4°C. Calcium (Ca) concentrations were determined with a Metrohm-Peak compact ion chromatograph (Herisau, Switzerland) at Montana State University. Detection limits were 5–10 μg l^{-1} and accuracy was within 5% of standards.

Cumulative DOC export

We calculated cumulative stream DOC export for the seven sub-catchments of the Tenderfoot Creek Catchment, and the three sub-catchments within the Stringer Creek Catchment. Daily stream DOC concentrations were estimated with linear interpolation between actual field measurements, and cumulative export was calculated for the 91-day study period (April 15–July 15, 2007). Cumulative stream DOC export for each sub-catchment within the Stringer Creek Catchment was estimated with the stream DOC concentration and discharge at that sub-catchment outlet after subtracting the contribution from the upstream catchments. To aid in comparison with other studies, we also estimated annual stream DOC export for the Stringer Creek Catchment. For the time outside of our study period of April 15–July 15, 2007, we used a baseflow DOC concentration of 1.6 mg l^{-1}, as measured before and after the snowmelt period.

Results

Landscape analysis

Across the three transects within the Stringer Creek Catchment, there were large differences in toeslope UAA, URS hydrologic connectivity, riparian width, and slope (Table 1). ST5-W had the largest UAA, widest riparian zone, and steepest hillslope. Riparian zone width and steepness of the hillslope were similar on ST1-E and ST1-W, but UAA was higher on ST1-E. Within the three sub-catchments in the Stringer Creek Catchment, there were differences in the proportion of riparian to upland area. The riparian zone comprised 3.8% of the catchment area between ST1 and MSC, and ~1.3% in the two other sub-catchments (Table 2). The percentage of the stream channel that exhibited URS hydrologic connectivity across the entire study period (April 15–July 15) was similar across each sub-catchment in the Stringer Creek Catchment, ranging from 69 to 76% (Table 2). For the sub-catchments within the Tenderfoot Creek Catchment, there was also a wide range in the proportion of riparian to upland area (Table 2). In general, SC, BC, and LSC had a small proportion of riparian to upland area (1.7–3.0%), MSC and LTC had an intermediate proportion (3.1–3.9%), and UTC and SP a high proportion of riparian to upland area (5.0–6.1%).

Snowmelt and precipitation

We present SWE and precipitation data from the Onion Park SNOTEL site (Fig. 3a, also shown in

Table 1 Stringer Creek transect characteristics of upslope accumulated area (UAA), hillslope–riparian–stream connectivity, riparian width, and slope of hillslope

Transect	UAA (m^2)	HRS connectivity (% of snowmelt)	Riparian width (m)	Hillslope (°slope)
ST1-E	10165	38	11.8	15.6
ST1-W	1563	0	12.7	12.5
ST5-W	46112	100	16.5	20.8

Hydrologic connectivity across the hillslope–riparian–stream (HRS) continuum was calculated by dividing the number of days that a hillslope water table was present by the total snowmelt period (April 15–July 15)

Table 2 UAA, percentage of stream network with upland–riparian–stream (URS) hydrologic connectivity, ratio of riparian:upland area, and cumulative stream DOC export from April 15 to July 15, 2007 for the three sections of Stringer Creek and the seven sub-catchments of Tenderfoot Creek

Stream section/sub-catchment	UAA (km^2)	HRS connectivity (% of catchment)	Riparian:upland (%)	Cumulative DOC export (kg ha^{-1})
HW–ST1	131	76	1.4	6.8
ST1–MSC	262	69	3.8	8.6
MSC–LSC	160	73	1.3	6.3
UTC	446	74	5.0	12.4
LTC	2260	66	3.9	11.4
MSC	393	71	3.1	8.1
LSC	550	72	3.0	8.4
BC	309	74	2.5	9.7
SC	352	76	1.7	9.5
SPC	400	57	6.1	11.9

Figs. 4, 5, 6) to represent general snowmelt timing. SWE peaked at 358 mm on April 20, 2007. The majority of the snowpack melted between April 27 and May 19, with average daily SWE losses of 15 mm and a maximum of 35 mm on May 13, 2007 (Jencso et al. 2009). A late spring snowfall event and subsequent melting between May 24 and June 1 yielded an additional 97 mm of water. Four days after the end of snowmelt, two rain events occurred (June 4–7, and June 13–18), totaling 30 and 22 mm, respectively.

Transect water table dynamics and DOC concentrations

We refer to our conceptual model of DOC export from the soil to the stream (Fig. 1) to present results of transect groundwater table fluctuations and DOC concentration dynamics in the context of soil DOC export processes. In Scenario 1, groundwater travels through low DOC mineral soil in the riparian zone during baseflow, and DOC inputs from the soil to the stream are low. As the groundwater table rises into shallow, DOC rich riparian soil during snowmelt or precipitation events, DOC inputs from the soil to the stream increase (Scenario 2). In Scenario 3, a hydrologic connection across the upland–riparian–stream continuum occurs. Once connectivity is initiated, a pulse of high DOC water is transmitted from the uplands to the stream along preferential flow paths (Scenario 3a). Low DOC upland matrix water traveling through mineral soil can then lead to dilution of DOC concentrations (Scenario 3b).

ST1-East

This transect had transient URS hydrologic connectivity, totaling 38% of the study period. DOC export from the soil to the stream likely occurred via all three scenarios in our conceptual model (Fig. 1), leading to both riparian and upland sources of DOC to the stream. At the riparian well, the groundwater table was initially low (Fig. 3b) and remained in mineral soil, leading to a low groundwater DOC concentration (1.4 mg l^{-1}) (Scenario 1). Riparian DOC concentrations increased at the end of April as the groundwater table quickly developed and entered shallow, DOC rich organic soil (Scenario 2). At the beginning of May, the groundwater table developed in the upland well (Fig. 3c), leading to a hydrologic connection across the upland–riparian–stream continuum (Scenario 3). At this time a DOC concentration of 5.8 mg l^{-1} was measured in the upland well. A quick pulse of DOC rich water from the uplands to the riparian zone along preferential flowpaths likely contributed to increased riparian DOC concentrations at the beginning of May (Scenario 3a). Upland DOC concentrations then quickly declined (to a minimum of 2.8 mg l^{-1} on May 14), leading to dilution of DOC concentrations in the riparian zone (Scenario 3b). The upland and riparian zone became hydrologically disconnected on May 20, and DOC dynamics in the

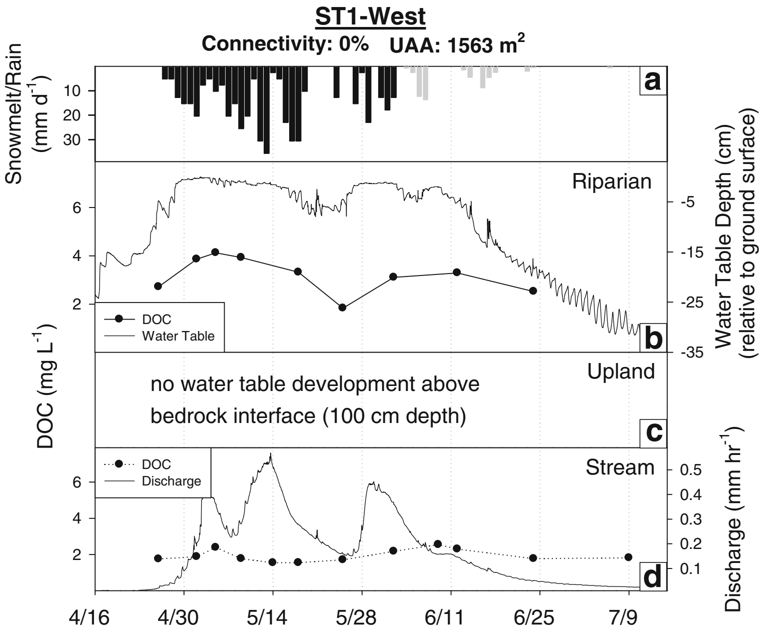


Fig. 4 **a** Soil water inputs from snowmelt (*black bars*) and precipitation (*grey bars*), **b** ST1-W riparian well DOC concentrations and groundwater height, **c** statement of no upland water table development above the bedrock interface at 100 cm, and **d** stream DOC concentrations and discharge from April 15 to July 15, 2007. The percentage of the study period that upland–riparian–stream connectivity existed, and upslope accumulated area (UAA) at the riparian measurement location are listed at the *top of the figure*. Stream discharge is from the Lower Stringer Creek Flume

riparian zone were no longer influenced by upland water (i.e. Scenario 3 ended). On May 26, the transient upland groundwater table was again initiated (return to Scenario 3), and riparian DOC concentrations increased (Fig. 3b). This increase in riparian DOC concentrations was concurrent with the rise in the riparian groundwater table, indicating the presence of Scenario 2. The upland groundwater table disconnected from the riparian zone after 8 days, then was not evident for the remainder of the study, and soil DOC export from the uplands ceased (end of Scenario 3). Riparian DOC concentrations decreased throughout June concurrent with the decline of the groundwater table into mineral soil (return to Scenario 1).

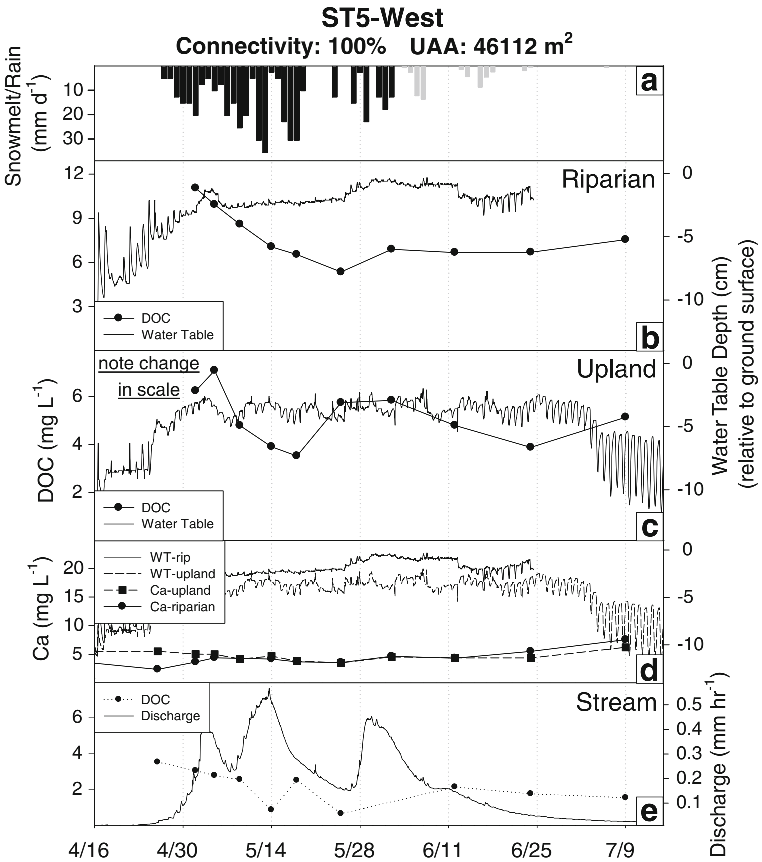
ST1-West

This transect never developed a hydrologic connection across the URS continuum (0% URS hydrologic connectivity) and it is likely that only Scenarios 1 and 2 from our conceptual model of DOC export from the soil to the stream occurred (Fig. 1). At the riparian well, the groundwater table was 15 cm below the ground surface at the beginning of snowmelt (Fig. 4b). DOC export occurred from relatively deep riparian soil (which likely had lower DOC concentrations than shallower soil) (Scenario 1), and a DOC concentration of 2.4 mg l^{-1} was observed. The groundwater table then rose into shallow, DOC rich riparian soil (reaching to within 1 cm of the ground surface by April 28), and DOC concentrations quickly increased to 4.2 mg l^{-1} (Scenario 2). The riparian water table declined between the middle and end of May and DOC concentrations decreased. The rise of the groundwater table at the end of May led to an increase in DOC concentrations, further indicating the presence of Scenario 2. The groundwater table then gradually declined to 30 cm below the ground surface by the middle of July (Fig. 4b), concurrent with a slight decrease in DOC concentrations. In general, DOC concentrations mimicked fluctuations in the riparian groundwater table.

ST5-West

This transect had 100% URS hydrologic connectivity for the duration of the study (persistent groundwater

Fig. 5 **a** Soil water inputs from snowmelt (*black bars*) and precipitation (*grey bars*), **b** ST5-W riparian well DOC concentrations and groundwater height, **c** ST5-W upland well DOC concentrations and groundwater height, **d** riparian and upland groundwater height and Ca concentrations, and **e** stream DOC concentrations and discharge from April 15 to July 15, 2007. Note the difference in scale for DOC at **b** and **c**. The percentage of the study period that upland–riparian–stream connectivity existed, and upslope accumulated area (UAA) at the riparian measurement location are listed at the *top of the figure*. Stream discharge is from the Lower Stringer Creek Flume



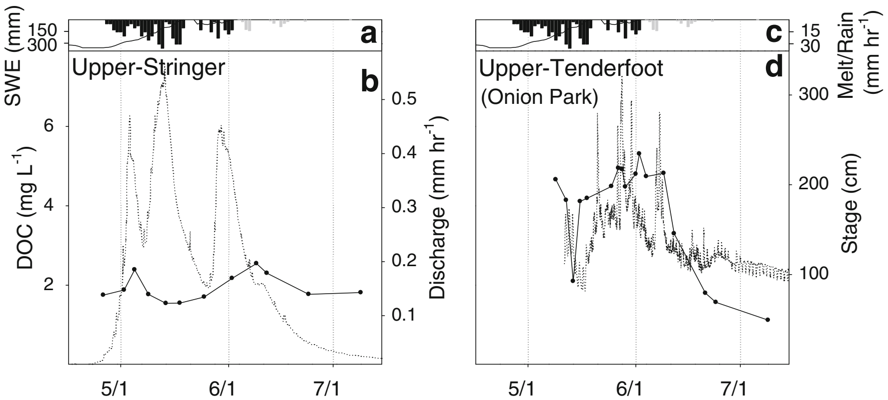


Fig. 6 **a** Soil water inputs from snowmelt (*black bars*) and precipitation (*grey bars*), **b** discharge and DOC concentrations at ST1 on Stringer Creek, **c** snow water equivalent and snowmelt, and **d** stage height and DOC concentrations at Upper Tenderfoot Creek (Onion Park) from April 15 to July 15, 2007. Discharge could not be calculated at Onion Park as no flume was installed

table in the upland well—Fig. 5c), and it is likely that DOC export dynamics from the soil to the stream remained in Scenario 3 of our conceptual model (Fig. 1) for the duration of the snowmelt period. At the riparian well, the groundwater table was 10 cm below the ground surface at the beginning of snowmelt, then rose into more organic DOC rich soil by the end of April (Fig. 5b), at which point DOC concentrations were high (11 mg l^{-1}). High riparian DOC concentrations at the end of April were also likely influenced by a large pulse of high DOC upland water that occurred with the rise of the upland water table (Scenario 3a). DOC concentrations then decreased concurrently in both the riparian and upland wells (Scenario 3b), further indicating the presence of a hydrologic connection across the upland–riparian–stream continuum and dilution of riparian DOC concentrations by low DOC water from the uplands. For the remainder of the study, the groundwater table remained relatively constant in both the riparian and hillslope wells (note that water table measurements ended on June 23 due to equipment malfunction), and small fluctuations of DOC concentrations were observed.

Calcium dynamics

We used Ca as a tracer to help differentiate between upland and riparian sources of DOC, and present measurements from ST1-E and ST5-W. At ST1-E, upland Ca concentrations were ~5 mg l^{-1} during the first initiation of the upland groundwater table at the beginning of May (Fig. 3d), and remained relatively constant throughout the study period (when groundwater was present). In contrast, Ca concentrations were high in the riparian zone at the beginning of snowmelt (18.4 mg l^{-1}, Fig. 3d). However, riparian Ca concentrations quickly declined to similar values observed in the uplands, indicating upland groundwater inputs to the riparian zone. On ST5-W, Ca concentrations were ~3–5 mg l^{-1} in both the riparian and upland wells for the duration of the study, indicating a constant hydrologic connection between the riparian and upland zones.

Stream discharge and DOC dynamics

Tenderfoot Creek

DOC concentrations were also variable along Tenderfoot Creek. At Onion Park, which drains a large network of wetlands near the headwaters of Tenderfoot Creek, DOC concentrations were relatively high (Fig. 6d). Note that stage and not discharge is shown at the outlet of Onion Park, as a flume was not installed here, and therefore no rating curve was available. While high DOC concentrations were observed during the early rise in flow (~4 mg l^{-1}), peak concentrations were not measured until the beginning of June, following the peak in flow. DOC concentrations then decreased coincident with the decline in flow, and reached a minimum value of 1.1 mg l^{-1} on July 9 (Fig. 6d).

At UTC, DOC concentrations were also high (Fig. 8). The stream DOC concentration was ~3 mg l^{-1} at the beginning of snowmelt, then increased by over 100% on the rising limb of the stream hydrograph. DOC concentrations fluctuated between 4 and 7 mg l^{-1} until the beginning of June, when concentrations quickly declined coincident with the recession to baseflow, and reached a minimum of 2.1 mg l^{-1} on July 9 (Fig. 8). At LTC, a similar trend was observed, however DOC concentrations were approximately half that measured at UTF and generally fluctuated between 2 and 4 mg l^{-1} (but decreased to 0.8 mg l^{-1} on May 23 following the large decline in discharge). The largest DOC concentration was measured on the falling limb of the last peak in discharge near the beginning of June.

Stringer Creek

DOC concentrations were highly variable along Stringer Creek (Fig. 7). At ST1, near the headwaters, DOC concentrations were relatively stable at ~1.8 mg l^{-1}, but increased near the beginning of May, associated with the first snowmelt-driven peak in stream discharge (Fig. 7a). DOC concentrations then declined during the first streamflow recession, and continued to decline during the second rise in stream discharge near the middle of May. Stream DOC concentrations at ST1 increased during the third and final rise in discharge, and continued to rise during the recession to baseflow, with a peak concentration of 2.6 mg l^{-1} on June 9.

At MSC, located between ST1 and ST5, stream DOC concentrations were more variable (Fig. 7b). A baseflow concentration of 1.4 mg l^{-1} was measured at the end of April. DOC concentrations nearly doubled by May 2, associated with the first snowmelt-driven peak in discharge. Concentrations remained high until May 15, when they began to decline coincident with the decrease in runoff, and reached a minimum value of 1.0 mg l^{-1} on May 23. DOC concentrations then sharply increased concurrent with the third snowmelt stream discharge peak.

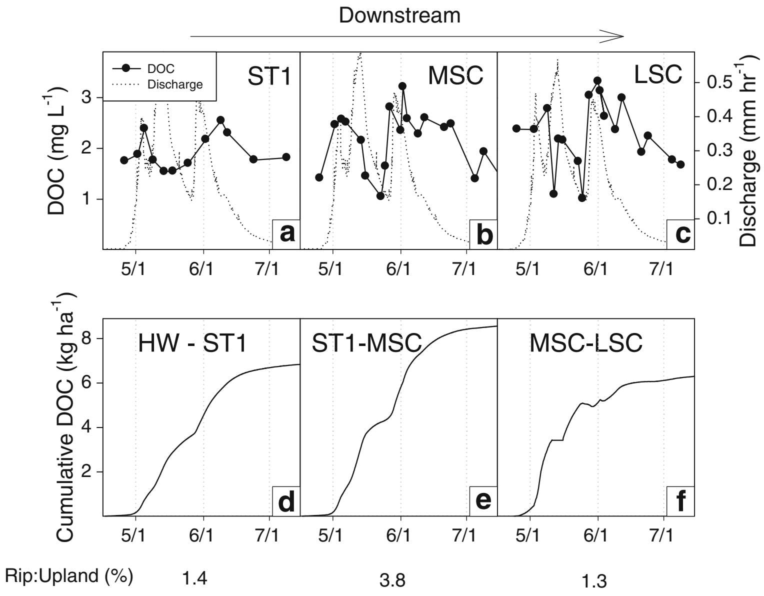


Fig. 7 **a–c** Upstream to downstream Stringer Creek DOC concentrations at **a** Transect 1, **b** Middle Stringer Creek Flume (MSC), and **c** Lower Stringer Creek Flume (LSC) from April 15 to July 15, 2007. **d–f** Cumulative DOC export from each sub-catchment. The percentage of riparian:upland extent within each sub-catchment is also shown

Concentrations remained at ~2.5 mg l^{-1} throughout June, and then returned to the baseflow concentration of 1.4 mg l^{-1} by the beginning of July (Fig. 7b).

At ST5, a peak streamflow DOC concentration of 3.5 mg l^{-1} was measured during the first sampling event on April 26 (Fig. 7c). DOC concentrations then quickly declined coincident with the peak in stream discharge. A sharp rise to 2.5 mg l^{-1} occurred on May 18 as discharge decreased. Stream DOC concentrations then declined to a minimum value of 0.6 mg l^{-1} on May 25, concurrent with the decrease in discharge at the end of May. DOC concentrations then increased following the rise in stream discharge after the late-spring snow event, and then decreased by the middle of July during the recession to baseflow. Note that stream DOC concentrations are not available for the June 2 and June 9 sampling events (Fig. 7c).

Stream DOC concentrations at LSC (catchment outlet) were 2.4 mg l^{-1} on the first sampling date at the end of April, rose slightly, and then declined to 1 mg l^{-1} by May 12, just before the peak in stream discharge (Fig. 7d). A brief rise occurred on May 14 (at peak discharge), then concentrations returned to 1 mg l^{-1} by the end of May as discharge decreased. DOC concentrations at LSC then quickly increased coincident with the rise in discharge at the end of May, and reached a peak of 3.3 mg l^{-1} at the beginning of June. Stream DOC concentrations fluctuated between 2 and 3 mg l^{-1} throughout June, then declined during the recession to baseflow (Fig. 7d).

Spring Park Creek

DOC concentrations were relatively low and similar to those measured at MSC and LSC (Fig. 8). Concentrations generally fluctuated between 2 and 3 mg l^{-1} throughout snowmelt, but declined to ~1 mg l^{-1} on both the rising and falling limb of the peak in stream discharge at the middle of May.

Sun Creek

Relative to other catchments, stream DOC concentrations were high (Fig. 8). At the beginning of snowmelt, a DOC concentration of 4 mg l^{-1} was measured, followed by a quick rise to a peak concentration of 7 mg l^{-1} on the rising limb of the initial peak in stream discharge. DOC concentrations declined to 2.8 mg l^{-1} following the decline in peak discharge at the middle of May. DOC concentrations then remained at ~5 mg l^{-1} until the beginning of June, when they decreased during the recession to baseflow, reaching a minimum of 2.5 mg l^{-1} by the end of the study period (Fig. 8).

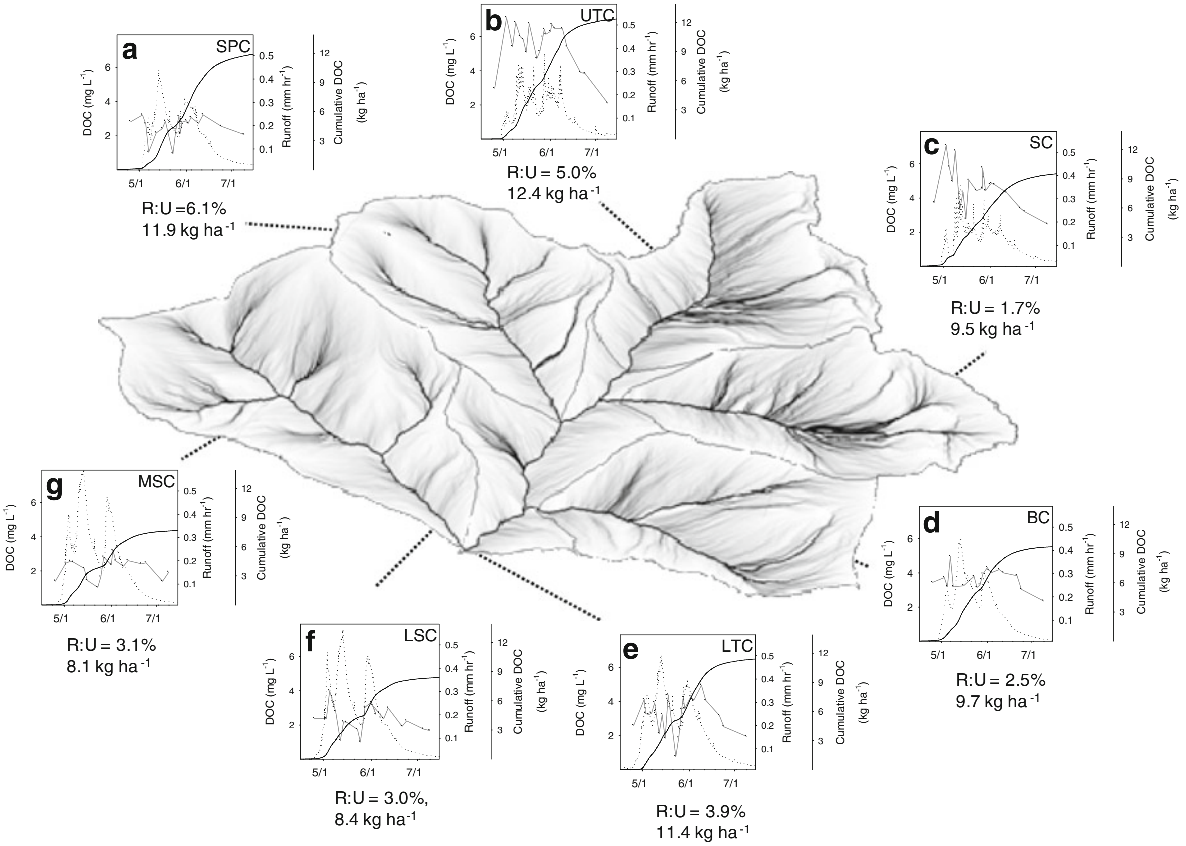


Fig. 8 Comparison of discharge, DOC concentrations, and cumulative DOC export at the catchment outlet of **a** Spring Park Creek, **b** Upper Tenderfoot Creek, **c** Sun Creek, **d** Bubbling Creek, **e** Lower Tenderfoot Creek, **f** Lower Stringer Creek, and **g** Middle Stringer Creek from April 15 to July 15, 2007. Riparian:upland extent (R:U) and cumulative stream DOC export is given for each sub-catchment

Bubbling Creek

DOC concentrations were stable and remained between 3 and 4 mg l^{-1} for the majority of the study period (Fig. 8). A peak concentration of 5 mg l^{-1} was measured at the beginning of May coincident with the rise in discharge at the beginning of snowmelt, and a minimum concentration of 2.3 mg l^{-1} was measured at the end of the study period as the stream receded to baseflow ($\sim$1 mm h^{-1}) (Fig. 8).

Cumulative stream DOC export

During the study period of April 15 to July 15, 2007, cumulative stream DOC was high for the ST1–MSC sub-catchment (8.6 kg ha^{-1}), while between 6.3 and 6.8 kg ha^{-1} at the other sub-catchments (Table 2; Fig. 7). For the larger sub-catchments of the Tenderfoot Creek Catchment, cumulative stream DOC export over the study period ranged from 8.1 to 12.4 kg ha^{-1} (Table 2). For the entire Stringer Creek Catchment, cumulative stream DOC for the entire 2007 water year was 9.6 kg ha^{-1}. There was a strong positive relationship ($r^2 = 0.67$, $p < 0.001$) between cumulative stream DOC export and the proportion of riparian to upland area across all sub-catchments (Fig. 9a). There was a negative (though insignificant) relationship between cumulative stream DOC export and the percent of the stream network with hydrologic connectivity at peak runoff ($r^2 = 0.28$, $p = 0.11$) (Fig. 9b).

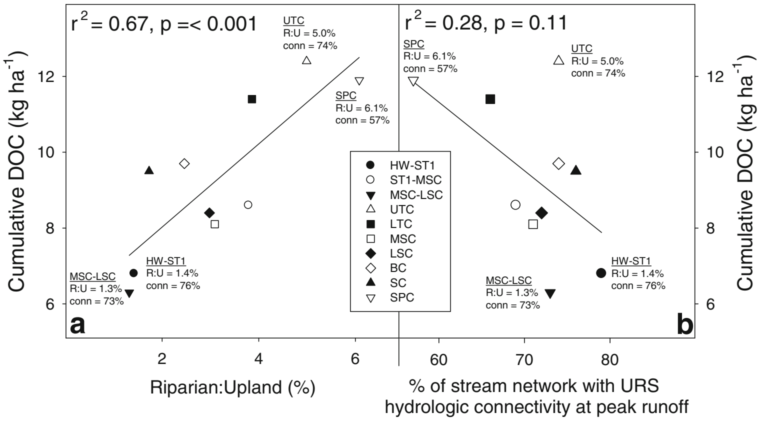


Fig. 9 Cumulative DOC export between April 15 and July 15, 2007 at each of the sub-catchments in the Tenderfoot Creek Watershed (including the three sub-catchments within the Stringer Creek Watershed) as a function of **a** riparian:upland ratio, and **b** percent of the stream network with URS hydrologic connectivity at peak runoff

Discussion

What are the dominant DOC source areas during snowmelt?

Hydrologic flushing is commonly referred to as the mobilization process that leads to a large release of DOC to the stream channel during snowmelt or precipitation events (Burns 2005). Both riparian and upland sources of DOC have been documented. For example, stream DOC concentrations can quickly increase at the beginning of snowmelt or precipitation events when a rising water table intersects shallow nutrient rich riparian zone soil (Fig. 1, Scenario 2) (Hornberger et al. 1994; Boyer et al. 1997, 2000; Laudon et al. 2004b). For export of DOC from organic rich riparian soil, a hydrologic connection is necessary between the riparian zone and the stream. A second source of DOC can become activated as a hydrologic connection develops across the entire upland–riparian–stream (URS) continuum (Fig. 1, Scenario 3) (McGlynn and McDonnell 2003; Bishop et al. 2004; Hood et al. 2006).

Our comparisons of DOC dynamics across three transects within the Stringer Creek Catchment illustrate the control of landscape structure on DOC export to the stream. ST1-W has a small toeslope UAA (1,563 m^2) (Table 1), and the water table never developed in the uplands (Fig. 4). This lack of URS hydrologic connectivity suggested that riparian soils would be the only source of DOC to the stream (McGlynn and McDonnell 2003). Our measurements of groundwater and DOC dynamics along ST1-W support this premise. DOC concentrations in the riparian well followed fluctuations in the groundwater table (Fig. 4b). At the beginning of snowmelt, concentrations increased as the water table rose to just below the ground surface and intersected shallow, DOC rich soils, then decreased during the initial decline in the water table. The relationship between increasing DOC concentrations and a rising water table in the riparian zone indicated riparian DOC export to the stream (Hornberger et al. 1994; Boyer et al. 1997, 2000; Inamdar and Mitchell 2006). DOC concentrations again increased coincident with the rise in the water table after a snowstorm and subsequent melt at the end of May, further supporting the occurrence of DOC export from the riparian zone. Export of DOC from upland soils was not apparent on ST1-W, since a hydrologic connection never developed across the URS continuum (i.e. no water table development in the upland well, Fig. 4c). Our measurements of water table and DOC dynamics at ST1-W indicate that in areas of small UAA and no URS hydrologic connectivity, riparian soils are likely the only source of DOC to the stream.

In contrast, we observed both riparian and upland DOC export on ST1-E, which had intermediate toeslope UAA (10,165 m^2), and transient URS hydrologic connectivity (for 38% of the snowmelt period) (Table 1). Riparian groundwater DOC concentrations increased at the beginning of snowmelt (Fig. 3b) as the water table rose into organic-rich shallow soils, indicating mobilization of DOC from the riparian zone (Hornberger et al. 1994; Boyer et al. 1997, 2000). However, water table development in the upslope well (Fig. 3d) resulted in hydrologic connectivity across the URS continuum (Jencso et al. 2009). URS hydrologic connectivity is supported by the convergence of riparian Ca concentrations to those measured in the uplands following the initiation of the upland groundwater table (indicating groundwater inputs from the uplands to the riparian zone) (Fig. 3d). DOC concentrations at the beginning of snowmelt were high in the upland well, and it is likely that this DOC-rich upland water was quickly transmitted along preferential flow paths (Freer et al. 2002; McGlynn and McDonnell 2003). This pulse of high-DOC upland water likely contributed to the increase in riparian groundwater DOC concentrations (Fig. 3b) (McGlynn and McDonnell 2003). After this initial rise in riparian DOC concentrations, continued URS hydrologic connectivity led to decreased concentrations due to dilution by low DOC matrix water from the uplands (McGlynn and McDonnell 2003). Riparian zone DOC concentrations then increased on May 20 following cessation of the upland water table and upland DOC contributions. The upland water table developed again on May 26 after a late-spring snowstorm (Fig. 3d). However, the water table in the uplands persisted for only a short period of time and did not lead to dilution of riparian zone DOC concentrations. Our measurements of water table and DOC dynamics along ST1-E indicate the presence of dynamic interactions between riparian and upland DOC export during snowmelt in an area of intermediate toeslope UAA and transient URS hydrologic connectivity.

Similar to ST1-E, both riparian and upland contributions of DOC from the soil to the stream were observed on ST5-W, which had a very large toeslope UAA (46,112 m^2). A hydrologic connection across the URS continuum was present for the entire study period, which is supported by nearly identical riparian and upland groundwater Ca concentrations (Fig. 5d). A riparian groundwater DOC concentration of 11 mg l^{-1} was measured near the beginning of snowmelt as the water table rose into shallow organic soil. However, it is likely that transmission of groundwater from the uplands also impacted DOC dynamics in the riparian zone due to constant URS hydrologic connectivity (McGlynn and McDonnell 2003). For example, DOC concentrations were high in the uplands following rise of the groundwater table at the beginning of snowmelt. DOC rich groundwater from the uplands was likely transmitted along preferential flowpaths to the riparian zone, thereby contributing to elevated riparian DOC concentrations. Following this initial rise in the groundwater table, DOC concentrations quickly declined at the riparian well even though the water table remained relatively constant (Fig. 5b). This decline was likely due to dilution from low DOC matrix water from the uplands, indicated by a similar decline in upland DOC concentrations. These results suggest that dynamic interactions between riparian and upland DOC export can occur in areas with persistent URS hydrologic connectivity.

Comparison of well and groundwater DOC dynamics on three transects with large differences in landscape setting and URS hydrologic connectivity demonstrated the range of riparian and upland DOC export from the soil to the stream that can occur through space and time in complex mountain catchments. In areas with small UAA and 0% URS hydrologic connectivity, only riparian DOC export was apparent. In contrast, both riparian and upland DOC export was evident in areas with higher UAA and transient to persistent URS hydrologic connectivity. We suggest that in complex snowmelt-dominated catchments, measurements of water table and DOC dynamics are necessary from a range of landscape settings in order to ascertain DOC source areas and mobilization and delivery mechanisms to the stream at the catchment scale.

How does the spatial extent and frequency of dominant landscape settings impact DOC export at the catchment scale?

The results of this study indicate that stream DOC export is dependent upon the spatial extent and organization of dominant landscape settings. Wetlands (Hope et al. 1994; Creed et al. 2003, 2008; Agren et al. 2007, 2008) and shallow riparian zone soil horizons (Bishop et al. 1994; Hood et al. 2006; Nakagawa et al. 2008) generally have high DOC content. Therefore, we would expect catchment areas with large riparian and wetland extent to be large DOC source areas. This premise was true in the TCEF, as illustrated in the comparison of DOC concentrations between the headwaters of Stringer Creek and Tenderfoot Creek (at Onion Park, Fig. 6). The headwaters of Stringer Creek have a relatively small riparian and wetland extent, and stream DOC concentrations were low ($\sim$1.5–2.5 mg l^{-1}). In contrast, the headwaters of Tenderfoot Creek have an extensive riparian and wetland network (with intermittent hydrologic connectivity to the stream) and therefore greater contributions from organic-rich soils. DOC concentrations at the headwaters of Tenderfoot Creek were generally >4 mg l^{-1} and therefore over 100% higher than at the headwaters of Stringer Creek. Further, there were large decreases in DOC concentrations in the headwaters of Tenderfoot Creek when flow declined at the middle of April and then again at the middle of June (Fig. 6). These decreases were likely the result of transient hydrologic connectivity between riparian and wetland DOC source areas. In contrast, the limited extent of riparian and wetland area had little effect on stream DOC concentrations at the headwaters of Stringer Creek during the transition from periods of high to low hydrologic connectivity. Our comparisons of both the timing and magnitude of stream DOC dynamics between the headwaters of Stringer Creek (little riparian and wetland area) and Tenderfoot Creek (large riparian and wetland area) indicate the strong influence that the spatial extent of organic-rich riparian and wetland areas can have on stream DOC export.

The influence of the extent of high DOC source areas on stream DOC export is also apparent when comparing the three sub-catchments of the Stringer Creek Catchment. Our results illustrate that even within a relatively small area (~550 ha), changes in the relative proportion of riparian to upland area can lead to strong differences in stream DOC export. At ST1, near the headwaters of Stringer Creek, stream DOC concentrations were low and relatively stable (Fig. 7a), resulting in low cumulative stream DOC export during snowmelt (6.8 kg ha^{-1}). These dynamics likely reflect the relatively small percent of riparian to upslope area (1.4%) within the Upper Stringer Creek Catchment (Table 2). Stream DOC concentrations increased downstream between ST1 and MSC (Fig. 7b), which was likely in response to the large increase in the percentage of riparian to upland area in this sub-catchment (3.8%, Table 2) (which was nearly three times higher than observed between the headwaters and ST1). This increase in the extent of organic riparian and wetland areas near the stream led to a large increase in cumulative stream DOC export from ST1 to MSC (8.6 kg ha^{-1}), and demonstrates the influence of large DOC source areas on stream DOC export. Cumulative stream DOC export was low between MSC and LSC (6.3 kg ha^{-1}), which had a riparian to upland extent of only 1.3%. This combination of low stream DOC export with a low proportion of riparian to upland area further supports the premise that the relative amount of riparian and wetland area is a strong control on DOC export.

Comparison of cumulative stream DOC to the proportion of riparian to upland area from each of the larger sub-catchments in the Tenderfoot Creek Catchment (Table 2; Fig. 8) also demonstrates the control of the relative size of high DOC source areas on stream DOC export at the catchment scale. The greatest DOC export generally occurred from catchments with high riparian to upland ratios. For example, cumulative stream DOC export was greatest from UTC and SPC (12.4 and 11.9 kg ha^{-1}, respectively). These catchments had the highest percentage of riparian to upland extent (5 and 6.1%). In contrast, cumulative stream DOC export was generally less than 10 kg ha^{-1} from catchments with smaller riparian to upland extents (ranging from 1.7 to 3.9%). The results of our study are supported by Hinton et al. (1998) and Inamdar and Mitchell (2006), who found that catchments with large wetland and riparian areas consistently had higher DOC concentrations than catchments with little to no riparian and wetland extent.

The results of our study also demonstrate how variability in internal catchment hydrologic dynamics can affect outlet DOC observations (Fig. 8). The Tenderfoot Creek Catchment is composed of seven sub-catchments, which varied in landscape structure (Jencso et al. 2009) and timing and magnitude of both stream discharge and DOC concentrations (Fig. 8). Stream discharge was low in both SC (Fig. 8b) and UTC (Fig. 8f), and almost never rose above 0.3 mm h^{-1}. At these catchments, stream DOC concentrations were very high (maximum concentrations of over 7 mg l^{-1} were observed). In contrast, peak discharge was approximately twice as high in Stringer Creek (at both MSC and LSC), and stream DOC concentrations never exceeded 4 mg l^{-1} throughout the study period. Further, while DOC concentrations increased on the rising limb of the stream hydrograph at all catchments, there was variability in the timing of peak DOC concentrations across the catchments (Fig. 8). There were also differences in DOC trends throughout the snowmelt period across the different catchments. In general, stream DOC concentrations were relatively stable in BC, MSC, and LSC, while concentrations were much flashier in SC and UTC (Fig. 8). At the outlet of Tenderfoot Creek (LTC), stream discharge and DOC dynamics were intermediate between the dynamics observed at the individual sub-catchments of Tenderfoot Creek, and reflect the integration of variability in landscape structure across the catchment (McGlynn and McDonnell 2003; Jencso et al. 2009). Our results indicate that DOC measurements at the outlet of a catchment are often an integration of internal dynamics and therefore may not be suitable for interpretation of DOC dynamics at different landscape positions within a catchment.

Intersection between size of DOC source area and degree of hydrologic connectivity

The results of this study demonstrate that both the degree of hydrologic connectivity between landscape elements and the size of DOC source areas are important controls on stream DOC export. Regression analysis of cumulative stream DOC export as a function of riparian to upland extent (Fig. 9a, $r^2 = 0.76$) and the percentage of the stream network with URS hydrologic connectivity at peak runoff (Fig. 9b, $r^2 = 0.28$) from the Tenderfoot Creek sub-catchments suggests that the relative extent of high DOC source areas was a stronger control on DOC export (higher r^2) than URS connectivity alone. For example, HW–ST1 and MSC–LSC (sub-catchments within the Stringer Creek Catchment) had a high degree of hydrologic connectivity across the upland–riparian–stream continuum (76 and 73%, Table 2; Fig. 9a), which suggested that cumulative stream DOC export would be high from these areas. However, DOC export was low, likely in response to the small proportion of riparian to upland area (i.e. relatively small DOC source area) (1.4 and 1.3%, Table 2; Fig. 9). In contrast, SPC had the lowest URS hydrologic connectivity of all sub-catchments (57%, Table 2; Fig. 9), suggesting that stream DOC export would be low. However, cumulative stream DOC export from SPC was high, likely in response to the high proportion of riparian to upland extent (6.1%, Table 2; Fig. 9a). These results demonstrate the importance of the relative size of a high DOC source area for soil DOC export to the stream.

The degree of hydrologic connectivity across the upland–riparian–stream continuum was not as strong of a predictor of stream DOC export. Of the sub-catchments of Tenderfoot Creek, the highest cumulative stream DOC export (12.4 kg ha^{-1}, Table 2; Fig. 9) occurred from UTC, which had both a high proportion of riparian to upland area and high URS hydrologic connectivity. We suggest that while both the size of the DOC source area and the degree of hydrologic connectivity are individually significant controls of DOC export from the soil to the stream, it is the intersection of the two that drives stream DOC export in complex terrain. Therefore, landscapes with both large DOC source areas and a high degree of URS hydrologic connectivity may be "hotspots" for stream DOC export in complex mountain catchments. We emphasize that the spatial organization and intersection of these variables is most important. For example, a catchment may have a large extent of high DOC source areas, but if these areas are rarely or never hydrologically connected to the stream, then stream DOC export may be lower than expected. Conversely, a catchment with a small extent of high DOC source areas may have high stream DOC export if these DOC source areas are well connected to the stream. We suggest that in order to accurately quantify the controls on stream DOC export at the catchment scale and predict DOC export dynamics, future research needs to examine both the size of DOC source areas and the degree of URS hydrologic connectivity, as well as their spatial organization.

Comparison to other studies

To aid in comparison with other studies, we estimated annual cumulative stream DOC export from the Stringer Creek Catchment. In a review of carbon export from nearly 100 catchments across the world, Hope et al. (1994) found a range of 10 to 100 kg ha^{-1} year^{-1} across a wide range of catchment sizes. Our estimate of cumulative DOC export from the Stringer Creek Catchment (9.6 kg ha^{-1} year^{-1}) is consistent with those from catchments of similar size ($\sim$5 km^2) and ecosystem type. However, Laudon et al. (2007) found that annual DOC export ranged from 35 to 76 kg ha^{-1} year^{-1} across seven catchments in northern Sweden, and Kortelainen et al. (1997) found a similar range across catchments in Finland. The site locations used for these studies were boreal catchments, which have very large stores of DOC (as indicated by stream DOC concentrations of up to an order of magnitude higher than observed in Stringer Creek), and likely explains the higher DOC export relative to our study site. Our results indicate that while stream DOC export from subalpine catchments may not be as high as from boreal catchments, they can still contribute a large flux of DOC, which can have large implications for ecosystem carbon balances (Laudon et al. 2004a; Neill et al. 2006; Johnson et al. 2006; Waterloo et al. 2006; Jonsson et al. 2007). We show that even within a relatively small area such as the Tenderfoot Creek Catchment, there was large variability in cumulative stream DOC export, which was partially controlled by differences in catchment structure. We suggest that variability in stream DOC export is likely to occur across catchments even within the same physiographic and bioclimatic regions because of differing landscape structures, which must be accounted for in estimates of ecosystem carbon balances.

Conclusions

Based upon catchment scale topographic analysis and measurements of stream and groundwater DOC dynamics during snowmelt (April 15–July 15) across three transects and seven catchments with a range of landscape settings and hydrologic connectivity between upland, riparian, and stream zones, we conclude that:

1. The relative importance of DOC source areas (riparian versus upland) on stream DOC export was dependent upon landscape position and the degree of hydrologic connectivity between the stream, riparian, and upland zones. Riparian DOC export was restricted to areas with a hydrologic connection across the riparian–stream (RS) interface, while a hydrologic connection across the entire upland–riparian–stream (URS) continuum was requisite for upland soil DOC export.
2. The relative importance of riparian versus upland DOC source areas on stream DOC export changed throughout space and time during snowmelt. In areas of small UAA and at times of low wetness status (such as baseflow), riparian zones were the dominant sources of DOC to the stream. In contrast, DOC contributions from upland soils were restricted to areas of larger UAA and times of increased wetness status (such as peak snowmelt). The relative importance of upland DOC source areas on stream DOC export increased after the initiation of snowmelt, with the greatest influence likely at peak snowmelt when the spatial extent of URS connectivity was highest throughout the catchment.
3. The intersection of hydrologic connectivity and high DOC source areas drove stream DOC export. The greatest DOC export occurred at areas with both high URS hydrologic connectivity and large DOC source areas.

This research provides insight into the spatial and temporal controls of DOC export from the soil to the stream during snowmelt. We suggest that landscape analysis coupled with multi-catchment analysis and integrated plot level measurements may provide a way forward in determining the relative importance of riparian versus upland sources of DOC on stream DOC export, and which areas of the landscape and which catchments likely provide the largest DOC contributions.

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References

Agren A, Buffam I, Jansson M, Laudon H (2007) Importance of seasonality and small streams for the landscape regulation of dissolved organic carbon export. J Geophys Res 112:G03003. doi:10.1029/2006JG000381

Agren A, Buffam I, Berggren M, Bishop K, Jansson M, Laudon H (2008) Dissolved organic carbon dynamics in boreal streams in a forest-wetland gradient during the transition between winter and summer. J Geophys Res 113:G03031. doi:10.1029/2007JG000674

Bishop K, Pettersson C, Allard B, Lee Y-H (1994) Identification of the riparian sources of aquatic dissolved organic carbon. Environ Int 20:11–19

Bishop K, Seibert J, Koher S, Laudon H (2004) Resolving the double paradox of rapidly mobilized old water with highly variable response to runoff chemistry. Hydrol Process 18:185–189

Boyer EW, Hornberger GM, Bencala KE, McKnight DM (1997) Response characteristics of DOC flushing in an alpine catchment. Hydrol Process 11:1635–1647

Boyer EW, Hornberger GM, Bencala KE, McKnight DM (2000) Effects of asynchronous snowmelt on flushing of dissolved organic carbon: a mixing model approach. Hydrol Process 14:3291–3308

Burns D (2005) What do hydrologists mean when they use the term flushing? Hydrol Process 19:1325–1327

Covino BL, McGlynn TP (2007) Stream gains and losses across a mountain-to-valley transition: impacts on watershed hydrology and stream water chemistry. Water Resour Res 43:W10431. doi:10.1029/2006WR005544

Creed IF, Sanford SE, Beall FD, Molot LA, Dillon PJ (2003) Cryptic wetlands: integrating hidden wetlands in regression models of the export of dissolved organic carbon from forested landscapes. Hydrol Process 17:3629–3648

Creed IF, Beall FD, Clair TA, Dillon PJ, Hesslein RH (2008) Predicting export of dissolved organic carbon from forested catchments in glaciated landscapes with shallow soils. Global Biogeochem Cycles 22:GB4024. doi:10.1029/2008GB003294

Farnes PE, Shearer RC, McCaughey WW, Hanson KJ (1995) Comparisons of hydrology, geology and physical characteristics between Tenderfoot Creek Experimental Forest (East Side) Montana, and Coram Experimental Forest (West Side) Montana. Final Report RJVA-INT-92734. USDA Forest Service. Intermountain Research Station, Forestry Sciences Laboratory, Bozeman, Montana, 19 p

Freer J, McDonnell JJ, Beven KJ, Peters NE, Burns DA, Hooper RP, Aulenbach B, Kendall C (2002) The role of bedrock topography on subsurface stormflow. Water Resour Res 38. doi:10.1029/2001WR000872

Hinton MJ, Schiff SL, English MC (1998) Sources and flowpaths of dissolved organic carbon during storms in two forested catchments of the Precambrian Shield. Biogeochemistry 41:175–197

Holdorf HD (1981) Soil resource inventory, Lewis and Clark National Forest, interim in-service report. On file with the Lewis and Clark National Forest. Forest Supervisor's Office, Great Falls

Hood E, Gooseff MN, Johnson SL (2006) Changes in the character of stream water dissolved organic carbon during flushing in three small catchments, Oregon. J Geophys Res 111:G01007. doi:10.1029/2005JG000082

Hope D, Billet MF, Cressner MS (1994) A review of the export of carbon in rivers: fluxes and processes. Environ Pollut 84:301–324

Hornberger GM, Bencala KE, McKnight DM (1994) Hydrologic controls on dissolved organic carbon during snowmelt in the Snake River near Montezuma, Colorado. Biogeochemistry 25:147–165

Imai A, Matsushige K, Nagai T (2003) Trihalomethane formation potential of dissolved organic matter in a shallow eutrophic lake. Water Res 37:4284–4294

Inamdar SP, Mitchell MJ (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

Inamdar SP, Christopher S, Mitchell MJ (2004) Flushing of DOC and nitrate from a forested catchment: role of hydrologic flow paths and water sources. Hydrol Process 18:2651–2661

Jencso KG, McGlynn BL, Gooseff MN, Wondzell SM, Bencala KE, Marshall LA (2009) Hydrologic connectivity between landscapes and streams: transferring reach and plot scale understanding to the catchment scale. Water Resour Res 45:W04428. doi:10.1029/2008WR007225

Jencso KJ, McGlynn BL, Gooseff KE, Bencala KE, Wondzell SM (in review) Hillslope hydrologic connectivity controls riparian groundwater turnover: implications of catchment structure for riparian buffering and stream water sources. Water Resour Res

Johnson MS, Lehmann J, Selva EC, Abdo M, Riha S, Guimarães Couto E (2006) Organic carbon fluxes within and streamwater exports from headwater catchments in the southern Amazon. Hydrol Process 20:2599–2614

Jonsson A, Algesten G, Bergstrom AK, Bishop K, Sobek S, Tranvik LJ, Jansson M (2007) Integrating aquatic carbon fluxes in a boreal catchment carbon budget. J Hydrol 334:141–150

Kortelainen P, Saukkonen S, Mattson T (1997) Leaching of nitrogen from forested catchments in Finland. Global Biogeochem Cycles 11:627–638

Laudon H, Kohler S, Buffam I (2004a) Seasonal TOC export from seven boreal catchments in northern Sweden. Aquat Sci 66:223–230

Laudon H, Seibert J, Kohler S, Bishop K (2004b) Hydrological flowpaths during snowmelt: congruence between hydrometric measurements and oxygen 18 in meltwater, soil water, and runoff. Water Resour Res 40:W03102. doi:10.1029/2003WR002455

Laudon H, Sjoblom V, Buffam I, Seibert J, Morth M (2007) The role of catchment scale and landscape characteristics for runoff generation of boreal streams. J Hydrol 344:198–209

McGlynn BL, McDonnell JJ (2003) Role of discrete landscape units in controlling catchment dissolved organic carbon dynamics. Water Resour Res 39. doi:10.1029/2002WR001525

McGlynn BL, Seibert J (2003) Distributed assessment of contributing area and riparian buffering along stream networks. Water Resour Res 39. doi:10.1029/2002WR001521

Mincemoyer SA, Birdsall JL (2006) Vascular flora of the Tenderfoot Creek Experimental Forest, Little Belt Mountains, Montana. Madrono 53:211–222

Nakagawa Y, Shibata H, Satoh F, Sasa K (2008) Riparian control on NO^{3-}, DOC, and dissolved Fe concentrations in mountainous streams, northern Japan. Limnology 9:195–206. doi:10.1007/s10201-008-0251-7

Neill C, Elsenbeer H, Krusche AV, Lehmann J, Markewitz D, de O, Figueiredo R (2006) Hydrological and biogeochemical processes in a changing Amazon: results from small catchment studies and the large-scale biosphere–atmosphere experiment. Hydrol Process 20:2467–2476

Pacific VJ, McGlynn BL, Riveros-Iregui DA, Welsch D, Epstein H (2008) Variability in soil CO_2 production and surface CO_2 efflux across riparian-hillslope transitions. Biogeochemistry. doi:10.1007/s10533-008-9258-8

Pacific VJ, McGlynn BL, Riveros-Iregui DA, Epstein HE, Welsch DL (2009) Differential soil respiration responses to changing hydrologic regimes. Water Resour Res. doi: 10.1029/2009WR007721

Riveros-Iregui DA, McGlynn BL (2009) Landscape structure controls soil CO_2 efflux variability in complex terrain: scaling from point observations to catchment scale fluxes. J Geophys Res Biogeosci. doi:10.1029/2008JG000885

Riveros-Iregui DA, McGlynn BL, Epstein HE, Welsch DL (2008) Interpretation and evaluation of combined measurement techniques for soil CO_2 efflux: surface chambers and soil CO_2 concentration probes. J Geophys Res Biogeosci. doi:10.1029/2008JG000811

Riveros-Iregui DA, McGlynn BL, Epstein HE, Welsch D, Marshall L (in review) A landscape-scale assessment of a process soil CO_2 production and transport model. J Geophys Res Biogeosci

Seibert J, McGlynn BL (2007) A new triangular multiple flow direction algorithm for computing upslope areas from gridded digital elevation models. Water Resour Res 43(4):W04501

van Vevrseveld WJ, McDonnell JJ, Lajtha K (2008) A mechanistic assessment of nutrient flushing at the catchment scale. J Hydrol 358:268–287

Waterloo MJ, Oliveira SM, Drucker DP, Nobre AD, Cuartas LA, Hodnett MG, Langedijk I, Jans WWP, Tomasella J, de Araújo AC, Pimentel TP, Múnera Estrada JC (2006) Export of organic carbon in run-off from an Amazonian rainforest blackwater catchment. Hydrol Process 20: 2581–2597

Wei Q, Feng C, Wang D, Shi B, Zhang L, Wei Q, Tang H (2008) Seasonal variations of chemical and physical characteristics of dissolved organic matter and trihalomethane precursors in a reservoir: a case study. J Hazard Mater 150:257–264

Wieler M, McDonnell J (2006) Testing nutrient flushing hypotheses at the hillslope scale: a virtual experiment approach. J Hydrol 319:339–356