Published March 13, 2015

Dissolved Organic Carbon Fluxes from Hydropedologic Units in Alaskan Coastal Temperate Rainforest Watersheds

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Dissolved organic C (DOC) transfer from the landscape to coastal margins is a key component of regional C cycles. Hydropedology provides a conceptual and observational framework for linking soil hydrologic function to landscape C cycling. We used hydropedology to quantify the export of DOC from the terrestrial landscape and understand how soil temperature and water table fluctuations regulate DOC losses in the C-rich, perhumid coastal temperate rainforest (PCTR) of Alaska. Land cover in the region is dominated by three major hydropedologic units: poor fen, forested wetland, and upland. We instrumented soils and streams in nine hydropedologic units to quantify DOC fluxes. Stream-water DOC concentrations varied from 5.7 to 16.7 mg C L^{-1}. Mean area-weighted DOC fluxes were 24.8, 29.9, and 10.5 g C m^{-2} yr^{-1} from the poor fens, forested wetlands, and uplands, respectively. We found that increased soil temperature and frequent fluctuations of soil water tables promoted the export of large quantities of DOC from poor fen and forested wetland units and relatively high amounts of DOC from upland units. The DOC export from the hydropedologic units in the PCTR is among the highest in the world and highlights the importance of terrestrial to aquatic fluxes of DOC as a pathway for C loss in the region.

Abbreviations: DOC, dissolved organic carbon; PCTR, perhumid coastal temperate rainforest.

The perhumid coastal margin of western North America extending from British Columbia to Kodiak Island in Alaska contains the largest contiguous expanse of perhumid coastal temperate rainforest (PCTR) in the world. The terrestrial ecosystems of the PCTR accumulated large amounts of soil C throughout the Holocene (Gorham et al., 2007). Mean C densities in the region exceed 300 Mg C ha^{-1} (Heath et al., 2011). About 66% of this C is belowground, where belowground C densities in wetlands are as high as 500 to 900 Mg C ha^{-1} (Leighty et al., 2006). This soil organic matter pool can deliver large quantities of dissolved organic C (DOC) to aquatic systems (Fellman et al., 2008). Understanding what controls DOC production and export from PCTR soils is particularly important for predicting the fate of this massive soil C stock under changing climate scenarios.

Soil terrestrial–aquatic linkages are facilitated by soil physical properties and soil chemical reactivity. The movement of DOC from soils to streams varies with the seasonal balance between DOC production and loss through physical and biotic processes and hydrologic transport via flow paths in the soil profile (Boyer

Supplemental material available online.

Soil Sci. Soc. Am. J. 79:378–388
doi:10.2136/sssaj2014.09.0380
Received 22 Sept. 2014.
Accepted 17 Jan. 2015.
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et al., 1997; Yano et al., 2000; Pastor et al., 2003; Emili and Price, 2006). Quantifying DOC flux in forested catchments has typically relied on estimating production in varying source areas (Hornberger et al., 1994; Dillon and Molot, 1997; Aitkenhead-Peterson et al., 2005; Lauerwald et al., 2012). A common strategy for examining DOC dynamics is to partition the landscape into functional groups according to soil type (Nelson et al., 1993; Canham et al., 2004; Creed et al., 2008). Wetlands and C-rich soils are thought to control the concentration of DOC in surface waters in a wide range of ecoregions (Mulholland and Kuenzler, 1979; Gorham et al., 1998; Frey and Smith, 2005; Aitkenhead and McDowell, 2000; Mulholland, 2003). However, wetland types vary considerably, and wetland inventories often focus on vegetative characteristics and neglect dynamic functional attributes such as DOC production and export. Therefore, a new approach that integrates hydrologic function and biogeochemical cycling in soils is needed to advance our understanding of DOC export at the watershed scale.

Hydropedology is a useful framework for advancing the understanding of soil hydrologic function at many scales (Lin et al., 2006; Lin, 2012) and explaining hydrologic and biogeochemical function in complex landscapes. Hydropedology is the multiscale investigation of the source, storage, flow path, residence time, availability, and spatiotemporal distribution of water in soils that occur in the Earth's critical zone (Lin, 2003). We used the hydropedologic approach to quantify the export of DOC from the landscape and to expand our understanding of the soil hydrologic processes that regulate this flux. Our goal in this research was to build on a proposed model of PCTR hydropedologic units (D'Amore et al., 2012) to quantify the flux of DOC from three hydropedologic units that dominate PCTR terrestrial ecosystems and are critical for understanding present and future terrestrial C cycle trajectories in the region.

MATERIALS AND METHODS

Site Description

The research was conducted in the perhumid coastal temperate rainforest of the Southeast Alaskan coast. Perhumid temperate rainforests are characterized by annual precipitation greater than 1400 mm, with >10% falling during cool summers and transient snow in the winter (Alaback, 1996). We replicated three hydropedologic units (poor fen, forested wetland, and upland) across three watersheds. The watersheds are located near Juneau, AK, and are part of a long-term C flux study in the North American Carbon Program (http://www.nacarbon.org; Fig. 1). Juneau has a temperate, maritime climate, with mean annual precipitation of 1580 mm and mean annual average temperatures ranging from 2 to 9°C. Significant rainfall occurs in all months of the year. We chose watersheds in three different ecological subsections that represent three distinct landscapes characterized by different lithology and dominant forms of landscape evolution (Nowacki et al., 2001). Peterson Creek watershed is a wetland-dominated watershed (53% of the watershed area) in the Stephens Passage glaciomarine terrace subsection that is primarily composed of slowly permeable glaciomarine sediments (Miller, 1973) along with bedrock outcrops that occur on moderate to low slopes. In contrast, McGinnis Creek watershed is primarily composed of recently deglaciated areas within the Boundary Ranges Icefield sub-

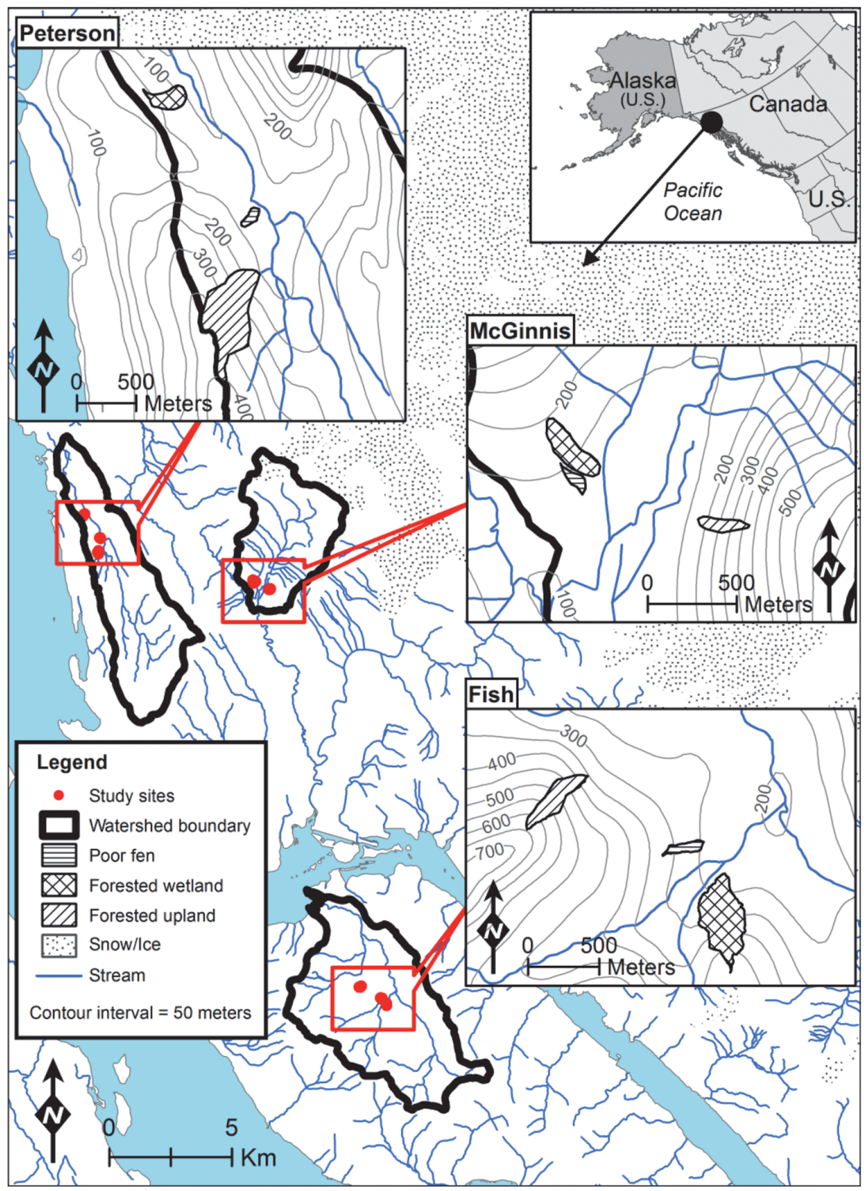

Fig. 1. Locations of the three hydropedologic units within three watersheds near Juneau, AK. The approximate locations of the three hydropedologic units (poor fens, forested wetlands, and uplands) are identified with dots within the larger watersheds (Peterson, McGinnis, and Fish creeks) boundaries. A larger illustration of the approximate size and relative location of each hydropedologic unit is provided in the enlargement of the area.

section and has low wetland coverage (<5% of the watershed area). Fish Creek watershed comprises intrusive volcanic and sedimentary rock in the Stephens Passage volcanic subsection and is a mix of physiographic features that include alpine, productive temperate rainforest, and wetlands.

Table 1. Distribution of total wetland area (%) and wetland classification within the Tongass National Forest in Southeast Alaska. Poor fens are in the palustrine emergent type and forested wetlands are in the palustrine forested type (data source: US Fish and Wildlife Service National Wetlands Inventory (NWI) GIS data set, provided by the US Forest Service, Tongass National Forest; table derived from US Forest Service, 2007).

NWI wetland type	Area	Proportion of all wetlands	Wetland component of total area
	ha	%	
Total wetlands	1,628,450	100.00	23.94
Palustrine forested	859,692	52.79	12.64
Palustrine emergent	408,816	25.10	6.01
Palustrine shrub-scrub	216,730	13.31	3.19
Palustrine unconsolidated bottom	20,921	1.28	0.31
Lacustrine	73,581	4.52	1.08
Riverine	19,606	1.20	0.39
Estuarine	26,231	1.61	0.29
Marine	3,680	0.23	0.05

Definition and Application of Hydropedologic Units

Gannon et al. (2014) offered a definition for hydropedologic units as "a grouping of variations in soil morphology that directly relate influence of water table regime, flow paths, and saturation to soil development." The concept that the presence and movement of water within a pedon and the movement of this water from the pedon to the surrounding environment transcends soil morphological theory and integrates soil hydrology with watershed hydrology is fundamental (Gannon et al., 2014; Lin et al., 2008). The forms of the hydropedologic units influence soil function, including biogeochemistry, runoff production, and vegetation diversity and structure. Hydropedologic units have been used to describe the interactions among soils and streams (Tetzlaff et al., 2014) and have been proposed as integrators of soil and stream hydrologic flow paths (D'Amore et al., 2012). Soil environments in the PCTR have distinct vegetation assemblages and soil horizonation. Therefore, identifying discrete hydropedologic units can elucidate how these forms influence the biogeochemical cycling and export of material from soils to streams.

We identified three hydropedologic units within each of the watersheds. They were chosen to cover the range of the most common hydropedologic units in the PCTR (Table 1). The three units are upland, forested wetland, and poor fen based on our understanding of hydrologic fluctuations with the specific soil types (D'Amore et al., 2010, 2015). We have maintained names for the hydropedologic units consistent with wetland classification categories of poor fen, forested wetland, and upland (Cowardin, 1979; National Wetlands Working Group, 1998; Table 2). The wetland categories are larger groupings of finer ecological divisions within these types in the inventories. Wetlands are roughly mapped in Southeast Alaska by the National Wetland Inventory and the National Land Cover Database, but there is no distinction in the hydrologic function and associated biogeochemical cycles of these wetland classes. Histosols and Inceptisols were present in both the poor fen and forested wetland hydropedologic units (Table 2), and the hydrologic control section was defined by the depth of the permanently saturated layer (D'Amore et al., 2010). Thus, these units are collectively referred to as "wetlands." In contrast, uplands were defined by a lack of near-surface soil saturation and are located on higher gradient slopes with zones of spodic mineral soil development. Subcatchments that were dominated by each of the three hydropedologic units were delineated within each of the three study watersheds for a total of nine subcatchments, with three replicates for each hydropedologic unit (Fig. 1).

Field and Laboratory Methods

A soil pit was excavated at each hydropedologic unit to a depth of 2 m or impermeable contact with either glacial till or bedrock. A companion soil probe survey was conducted to as-

Table 2. Soil classification and physical attributes of the three hydropedologic units within Fish, McGinnis, and Peterson creeks watersheds near Juneau, Southeast Alaska.

Watershed	Hydropedologic type	Taxonomic classification†	Elevation	Slope	C stock‡	Drainage class§
			m	%	Mg C ha^{-1}	
	poor fen	Typic Cryohemist	253	6.6	556	very poorly drained
Fish Creek	forested wetland	Terric Cryohemist	240	15.5	376	poorly drained
	upland	Typic Haplocryod	392	19.4	245	well-drained
	poor fen	Typic Cryohemist	137	5.2	527	very poorly drained
McGinnis Creek	forested wetland	Terric Cryohemist	133	7.6	1023	somewhat poorly drained
	upland	Typic Humicryod	179	19.0	290	well drained
	poor fen	Typic Cryohemist	111	3.9	651	very poorly drained
Peterson Creek	forested wetland	Histic Cryaquept	109	9.8	388	poorly drained
	upland	Lithic Haplocryod	190	18.7	242	well drained

† Classification represents the field and laboratory interpretation for the site, not the official series.

‡ Total average pedon C stock.

§ Determined by field observations and soil map unit assignment from soil resource inventory.

sure general soil homogeneity across the hydropedologic catchment area. Soil genetic horizons were delineated, described, and sampled following the protocol of Soil Survey Division Staff (1993). Soil characterization analysis was performed according to standard methods (Soil Survey Laboratory Staff, 1996) unless otherwise specified. Bulk density for mineral soils and organic soil field samples were taken in triplicate 125-cm^3 cubes or rings, weighed, dried, and reported as dry weight per unit volume (g cm^{-3}). Total C contents were determined on pulverized samples in a Leco CHN analyzer. Soil pedons were classified on site using soil descriptions and then correlated with laboratory data (Table 2; Soil Survey Staff, 1999).

Stream-water samples were collected in the small outlet stream draining each hydropedologic unit. Soil solution was taken from piezometer wells constructed of 3.2-cm polyvinyl chloride (PVC) pipe, slotted at depths of 25 and 50 cm. Stream-water and soil-solution samples were field filtered using precombusted, Gelman A/E glass fiber filters and stored at 4°C in acid-washed high-density polyethylene bottles until DOC analysis within 1 wk of collection. Concentrations of DOC were analyzed using high-temperature combustion on a Shimadzu TOC/TN-V analyzer. Samples were collected weekly during the spring, summer, and early fall and then biweekly to monthly during the winter over the course of 1 yr (2006). The depth to water table was measured in pairs of wells installed adjacent to the soil-solution piezometers. Water table wells were constructed by drilling paired holes at 1-cm intervals along the length of schedule 40 PVC pipe (3.2-cm i.d.) and were installed to the 50-cm depth. Water level in the wells was recorded at 15-min intervals and then averaged to hourly readings with Solinst LeveLoggers. The level recorded in the two wells was averaged to produce a single value for the subcatchment. The wells were continuously measured for a 1-yr period. Flow gauging Parshall flumes (Plasti-Fab) were installed in outlet streams draining each subcatchment site to quantify water flow from the hydropedologic unit. Each flume was equipped with an unvented pressure transducer (Solinst LeveLogger) that measured the water height in the flume every 15 min. Transducers were corrected for atmospheric pressure changes by barometric pressure transducers (Solinst LeveLogger) at the site. In the case of missing or erroneous barometric data, atmospheric readings from a local NOAA barometric station were used for corrections. Flow estimates were made at the flumes unless the stream water was frozen. Flume stage was converted to volumetric discharge using manufacturer-supplied rating curves.

Calculation of Stream-Water Dissolved Organic Carbon Flux

Stream-water DOC flux from each hydropedologic unit was calculated from continuous discharge measurements combined with regular (weekly to biweekly) stream-water samples of DOC concentration. Concentration–discharge relationships to determine DOC flux were calculated using the load estimator program LoadEst (Runkel et al., 2004). Data input and output were facilitated by use of the Loadrunner program (Raymond and Saiers, 2010; http://environment.yale.edu/loadrunner/loadrunner/readers/discussion.html). The program was calibrated with all paired concentration and discharge measurements from each hydropedologic type. The program was then used to interpolate concentration values and calculate daily DOC loads (kg d^{-1}) by applying the best fit among nine models available in the LoadEst program environment (Supplemental Table S1). The flux of DOC was calculated with adjusted maximum likelihood estimation through a nonlinear regression, with the measured DOC concentration and measured stream discharge as dependent and independent variables, respectively (for details, see Runkel et al., 2004). Daily flux estimates were summed for each subcatchment, and area-weighted fluxes were derived by normalizing the annual DOC flux by the watershed area of the subcatchment.

Statistical Analyses

We tested the influence of the hydropedologic unit (poor fen, forested wetland, and upland) on the average monthly soil water table depth. We accounted for the measurements replicated in time by using a mixed model analysis (SAS Version 9.2, Proc Mixed procedure), with hydropedologic unit and time as fixed effects and treatments nested within sites as a random effect. We chose a compound symmetry covariance structure after evaluating various other covariance structure options. All ANOVA and regression analyses were completed using Sigmaplot Version 11.

RESULTS

Soil Hydrodynamics and Stream Discharge

There was a significant difference in the depth to water table among the hydropedologic units ($F_{(2,4)} = 23.80$, $P = 0.006$; Fig. 2). The water table was lower in the upland units than the forest-

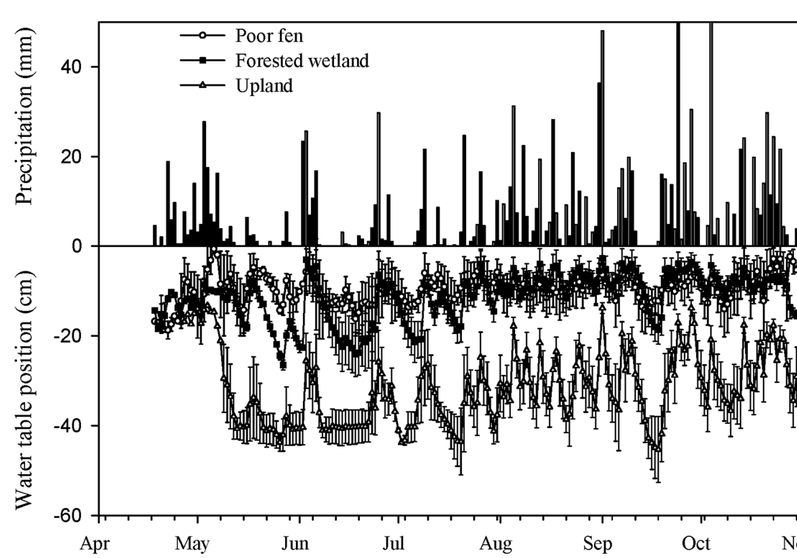

Fig. 2. Precipitation and average daily soil water position (±SE) in the soils of three hydropedologic units (poor fens, forested wetlands, and uplands) from April to November of 2006.

ed wetland and poor fen units (Fig. 2). The maximum depth of the water table was greater in the forested wetlands than the poor fens, but there was no statistically significant difference between the water tables of these two units. The depth to water table also varied by time of measurement ($F_{(12,68)} = 4.71$, $P < 0.001$; Fig. 2), with deeper water tables in late spring and early summer in all units. Although depth to the water table varied seasonally and between the upland and wetland hydropedologic units, the drop in water table positions within the soils was similar. Water table reductions occurred at similar rates among all three units during dry periods, but in the wetlands the water table did not drop as far and recharge was rapid once precipitation resumed (Fig. 2).

Stream discharge varied with water table depth across all units (Fig. 3). The poor fens and forested wetlands had a threshold in the relationship between water table position and runoff generation, with very little runoff generated at low water table positions and a transition to runoff generation at higher water tables (Fig. 3). Discharge varied with water table depth in upland sites but there was more variability in the depth–discharge relationship relative to the wetland sites. All upland sites had water discharging at deeper water table depths, with the Peterson Creek unit exhibiting a threshold similar to the wetland units. McGinnis Creek and Fish Creek upland units had more linear depth–discharge relationships, and the McGinnis Creek unit had little evidence of a threshold.

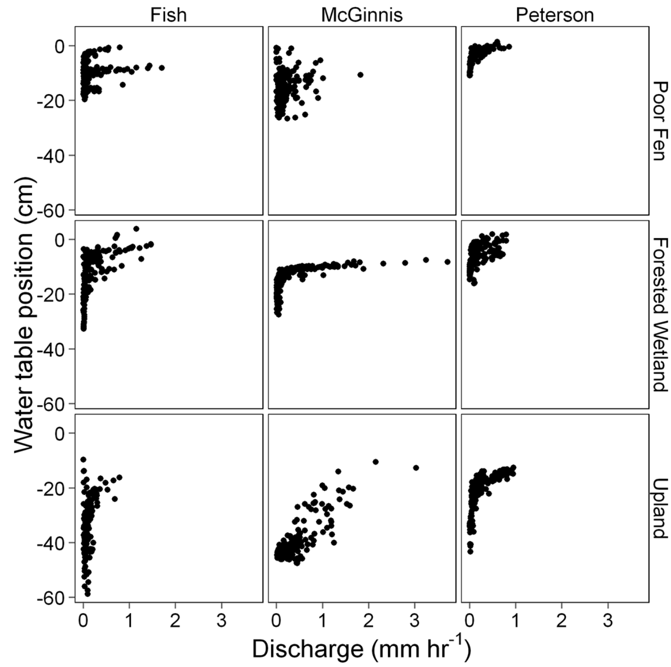

Fig. 3. Relationship between water table position below the soil surface and stream discharge in each hydropedologic unit at all three watershed locations.

Soil Carbon Stocks and Production of Dissolved Organic Carbon among Soil Hydropedologic Units

Soil C stocks are large in all the hydropedologic units, with an increase from the uplands (242–290 Mg C ha^{-1}) to forested wetlands (376–1023 Mg C ha^{-1}) and poor fens (527–651 Mg C ha^{-1}; Table 2). The main storage location for C in all sites are the organic horizons, which typically extend to the 0.2-m depth in uplands, more than 0.5 m deep in forested wetlands, and beyond 1.0 m in the poor fens. The soil C concentration in the wetland units is reflected in the soil taxonomic classifications of Hemist suborders and the Histic subroup designation (Table 2). Upland soils have organic surface horizons that range from 10 to 17 cm deep, but only one soil classified in the Humicryod Great Group; the other two units were Haplocryods (Table 2).

In hydropedologic unit outlet streams, DOC concentration was related to soil C stock, soil temperature, and soil saturation. Mean stream-water DOC concentration was significantly related to the soil C stock across all sites ($F_{(7,8)} = 6.87$, $P = 0.03$). Stream-water DOC concentrations in the wetland hydropedologic units were two to three times greater than concentrations in upland streams, reflecting the strong relationship between soil C stocks and DOC (Fig. 4). Mean monthly stream-water DOC concentrations increased with increasing soil temperatures in the poor fen and forested wetland units (Fig. 5). In contrast, there was no apparent relationship between stream-water DOC and soil temperatures in the upland units (Fig. 5). However, increased upland stream-water DOC concentrations in August and September were associated with water table fluctuations caused by more frequent rainstorms than earlier in the summer (Fig. 2).

Soil water DOC concentrations varied seasonally with temperature at the 25-cm depth in all hydropedologic units (Fig. 6). Soil water DOC concentrations increased from April to their

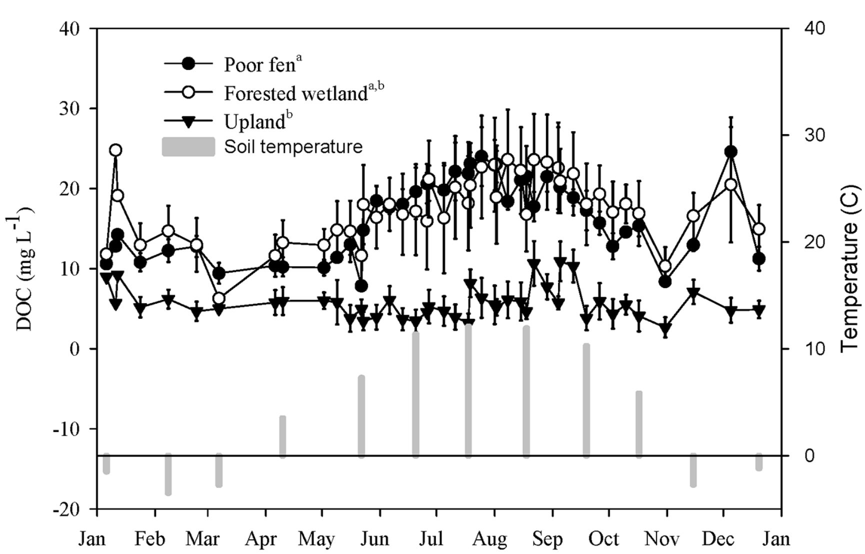

Fig. 4. Mean (*n* = 3) stream-water dissolved organic C (DOC) concentrations in three hydropedologic units during the ice-free season in Southeast Alaska. Letters next to each hydropedologic unit represent statistical differences at α = 0.05 in the ANOVA test.

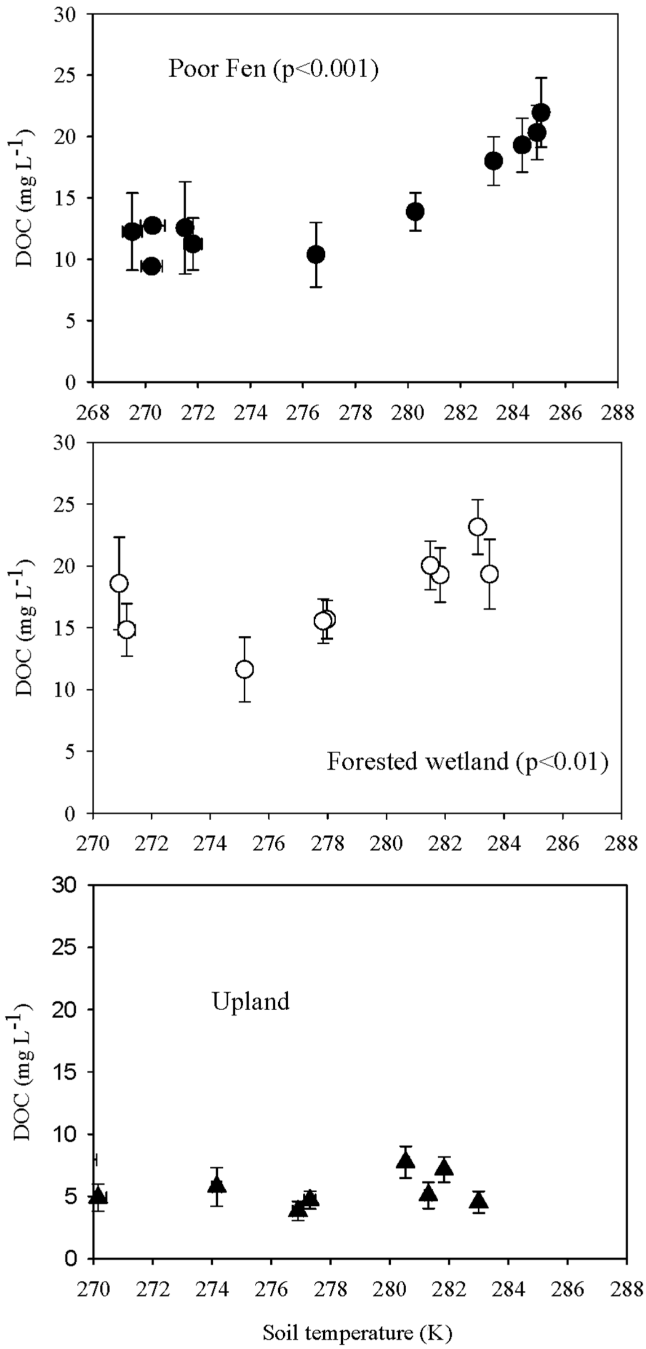

Fig. 5. Relationship between mean (±SE) soil temperature and mean (±SE) stream-water dissolved organic C (DOC) concentrations for the classes of the hydropedologic units. There is a nonlinear relationship between soil temperature and DOC concentration in the poor fens. There is a linear relationship between soil temperature and DOC concentration in the forested wetlands at temperatures >273 K. There is no relationship between temperature and DOC in the uplands.

seasonal maxima in July and August across all hydropedologic units. Concentrations of DOC then decreased steadily from August to October or November across all units. The pore-water concentrations were generally highest in the forested wetlands, lower in the poor fens, and lowest in the uplands (Fig. 6). Pore-water DOC concentrations were elevated at the 50-cm depth in the spring and then declined steadily during the summer to their low levels in late fall (Fig. 6). The DOC concentration was

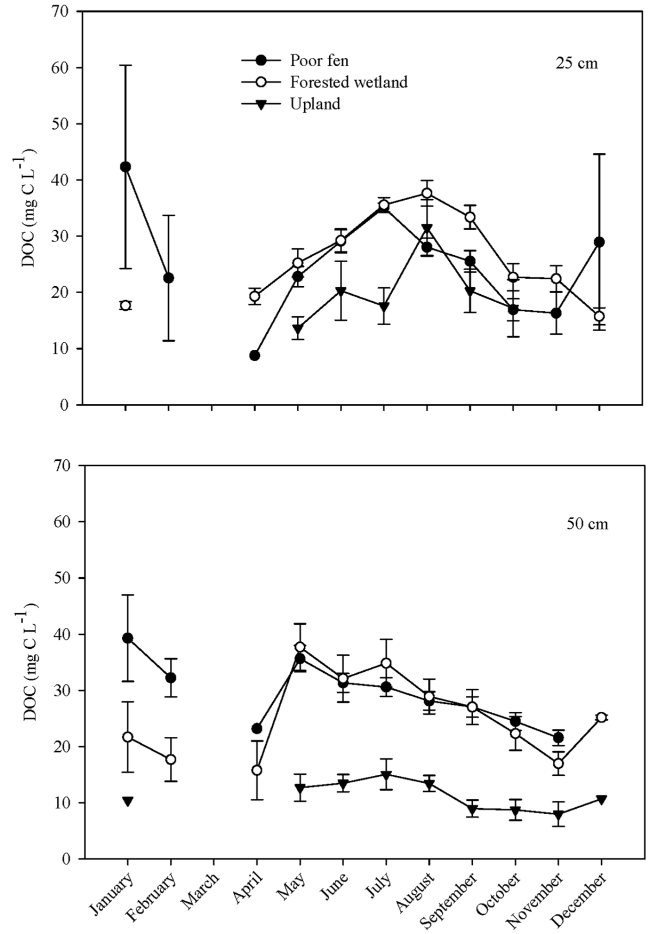

Fig. 6. Seasonal patterns of soil dissolved organic C (DOC) concentrations in poor fens, forested wetlands, and uplands. Measurements were taken at the 25- and 50-cm depths. The soil solution concentrations are means ± SE (*n* = 3 per hydropedologic unit). The data gap in March is due to missing samples during this period.

also high in January in the poor fens. Soil solution DOC concentrations at the two depths differed in their relationship with water table position. At the 25-cm depth, there was a consistent increase in concentration in the wetland units as the water table dropped during June and July. In the uplands, where water levels were consistently low, DOC concentrations also increased during the same time period. At the 50-cm depth, concentrations decreased along with the water table in the wetland sites but not at the upland sites (Fig. 6). The rise in water tables at all sites in August to October was associated with a downward trend in DOC concentration at both depths (Fig. 2 and 6).

Stream-Water Dissolved Organic Carbon Fluxes

Average area-weighted DOC flux (i.e., specific DOC flux) ranged from 10.5 to 29.9 g C m^{-2} yr^{-1} across the hydropedologic units (Table 3). Monthly mean DOC export from the three units increased from midwinter (January–March) through the summer, followed by a decrease in flux in late October, reflecting differences in soil C stocks between the units and the patterns in soil and stream-water DOC concentrations (Fig. 7). Most (52–60%) of the annual flux occurred during August, September, and October (Fig. 7). The maximum DOC flux observed in the hydropedologic units was later than the peak in stream-water DOC concentration. Stream-water DOC concentrations in the forested wetland and poor fens peaked in late July and early August; however, DOC fluxes were highest in September for these units. Upland hydropedologic unit stream-water concentrations were highest in late August and September, which more closely aligns with peak DOC fluxes (Fig. 4 and 7). Overall, the DOC concentration in stream water and soils was associated more closely with temperature, whereas the DOC flux was related to the consistent patterns of higher water table position within the hydropedologic units.

DISCUSSION

Hydropedologic Units as Dissolved Organic Carbon Sources in the Perhumid Coastal Temperate Rainforest

The large soil C stocks of the PCTR and their potential sensitivity to climate warming make it essential to understand the current magnitude of DOC export from PCTR watersheds and how it may change with climate. Dissolved organic C export is also an essential component for balancing watershed C budget models in temperate regions (Neff and Asner, 2001). The average annual DOC fluxes from the main hydropedologic units in the PCTR are greater than most fluxes previously reported for comparable peatland and upland forested watersheds (Clair et al., 1994; Hope et al., 1997; Canham et al., 2004), highlighting the strong potential for the redistribution of soluble C from terrestrial ecosystems to coastal waters within this region. Moreover, the DOC flux from upland soils in the PCTR (10.5 g C cm^{-2} yr^{-1}; Table 3) is more than 30% larger than the estimated average annual flux from terrestrial ecosystems worldwide (i.e., 7.7 g C cm^{-2} yr^{-1}; Randerson et al., 2002). The only peatland ecosystems of which we are aware with comparable rates of DOC export are the Indonesian peatlands, with C export values equal to or exceeding the estimates for the catchments in this study (Baum et al., 2007; Aldrian et al., 2008).

Using hydropedologic units to quantify DOC flux assumes that their hydrologic and biogeochemical behavior is predictable and driven by quantifiable underlying mechanisms. Dissolved organic C flux can be described by integrating soil type, temperature regime, precipitation, and soil saturation (Clair et al., 2013; Bengtson and Bengtsson, 2007). Therefore, our findings related to mechanisms of DOC generation in the dominant PCTR hydropedologic units and our DOC flux estimates for these units fill a critical information gap and provide a framework to evaluate changes in regional DOC fluxes with time.

Soil Hydrodynamics as Defining Concepts for Hydropedologic Units in the Perhumid Coastal Temperate Rainforest

In the cool, wet climate of the PCTR, topographic position exerts a dominant influence on soil saturation and organic matter accumulation (Neiland, 1971; D'Amore et al., 2012). Wetlands are abundant on flatter slopes where water from upslope accumulates and soil water velocities decrease, resulting in electrochemically reducing, anaerobic conditions that favor organic matter accumulation (D'Amore et al., 2010). Soil horizonation in the forested wetland and poor fen hydropedologic units is caused by the accumulation of plant detritus above permanently saturated humified material. A long-standing model of peatland soil development separates the soil profile into a permanently saturated, slowly decomposing lower layer (catotelm) and an intermittently saturated, faster decom-

Table 3. Mean stream-water dissolved organic C (DOC) concentrations and annual DOC export among nine hydropedologic units near Juneau, AK. Average values are based on the three individual hydropedologic types in the study.

Watershed and hydropedologic unit	Area	DOC	DOC export
	ha	mg L^{-1}	g C m^{-2} yr^{-1}
Peterson Creek			
Poor fen	1.3	17.5	20.1
Forested wetland	5.5	15.2	20.7
Upland	23.7	6.6	9.0
McGinnis Creek			
Poor fen	0.9	22.8	24.4
Forested wetland	4.3	27.1	49.8
Upland	1.1	3.7	5.9
Fish Creek			
Poor fen	1.3	18.1	29.8
Forested wetland	12.9	24.6	19.4
Upland	6.8	13.9	16.6
Avg. poor fen	1.2 (0.1)†	19.5 (1.7)	24.8 (2.8)
Avg. forested wetland	7.7 (2.6)	22.3 (3.6)	29.9 (9.9)
Avg. upland	10.5 (6.8)	8.1 (5.2)	10.5 (3.2)

† Standard error in parentheses.

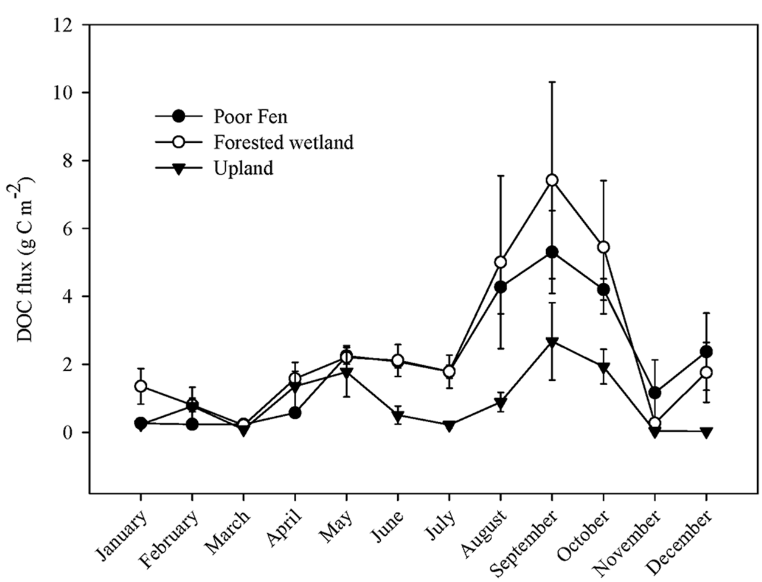

Fig. 7. Mean (±SE) monthly dissolved organic C (DOC) flux derived from average fluxes (sampled every 1–3 wk) among replicate hydropedologic units. The months of August, September, and October account for 56, 60, and 52% of the annual DOC flux from the poor fen, forested wetland, and upland hydropedologic units, respectively.

posing upper layer (acrotelm; Ivanov, 1953; Ingram, 1978). Shortcomings of this diplotelmic model have been identified and extensions proposed (for a review, see Morris et al., 2011). We observed substantial changes in hydrologic function within the intermittently saturated upper layer, the acrotelm (Fig. 3). Therefore, our results are consistent with a model proposed by Morris et al. (2011) in showing a hydrologically active upper layer and hydrologically inactive lower layer in the poor fen and forested wetland hydropedologic units. In this case, hydrologic activity is based on differences in hydrologic conductance and the contribution to discharge between the shallow and deep layers. We will therefore refer to the surface layer as the *active* layer and the deeper humified layer as the *inactive* layer based on their conductivities and influence on stream discharge.

Although wetlands typically occur on flatter portions of the landscape relative to uplands, they do occur on slopes high enough (~15%) to rapidly generate stream discharge. Rainfall can be rapidly converted to runoff in PCTR catchments because surface organic horizons are permeable and watersheds in the Coast Mountains are steep. In this environment, once a sufficient layer of inactive, humified peat accumulates, it creates a positive feedback loop that encourages more peat accumulation. The inactive layer holds water like a sponge and is normally saturated even when the overlying peat dries out through drainage and increased evapotranspiration. Thus the inactive layer sets a lower boundary for water table depth and determines the volume of the active layer wherein C mineralization and lateral transport occur. Although wetland soils are considered "poorly drained," water tables in the active layer rise and fall at rates comparable to the uplands (Fig. 2) but with lower limits controlled by the depth of the inactive layer.

Following the soil hydrology model described above, wetland soils in the PCTR are saturated not just because they occupy level locations but because a thick layer of nonconductive peat holds water year-round regardless of the soil slope. Above the inactive layer, the thinner porous surface horizon dynamically stores and releases water and solutes, but its water storage capacity relative to rainfall and groundwater inputs is low because of the presence of the inactive aquitard. Therefore, although the active layer is actually well drained, it is seasonally saturated because its storage volume is low and the generation of discharge requires the water table to reach the active upper layer (Herendeen, 2014). The key difference between the forested wetlands and poor fens is the thickness of the conductive layer and the depth to the water table, with a much thinner active layer in poor fens (D'Amore et al., 2010). This is a key defining concept in the distinction of the wetland hydropedologic units in the PCTR.

Production of Dissolved Organic Carbon in Soil Solution

The dynamic wetting and drying of the active layer in PCTR wetland soils creates conditions that favor the generation and transport of DOM to adjacent streams. Wetland water tables fall in early to midsummer when reduced precipitation coincides with increased plant water demand (Fig. 2). Temperature alone does not fully predict stream DOC concentration and export, as warm temperatures that produce peak soil solution DOC concentrations don't always coincide with effective hydrologic transport. Rainfall events that do not raise the water table into the hydrologically active zone produce slower, yet persistent flow, with smaller amounts of the soluble DOC pool reaching the stream. When the water table is elevated into the hydrologically active horizon, lateral flow through the entire layer is generated and larger amounts of DOC are rapidly flushed to the adjacent stream. This results in extremely high DOC fluxes from wetland units during storms (Fellman et al., 2009). Similar discharge–peat structure relationships have been observed in a prior study in the same area (D'Amore et al., 2010) and in UK peatlands (Holden and Burt, 2003; Worrall et al., 2004; Tetzlaff et al., 2014). Large DOC fluxes within wetland soils occur when increased soil DOC availability coincides with high lateral soil water flow. These functions do not occur simultaneously. Soil C mineralization is greater when water tables are lower, increasing the volume of the warm, unsaturated, aerobic soil surface layer, whereas lateral water flow is highest when the active layer is saturated, at which time the active layer becomes anaerobic and mineralization decreases (Fig. 3; Mitchell and Branfireun, 2005; D'Amore et al., 2010).

Overall, our results are consistent with the idea that lateral DOC fluxes from PCTR soils increase during conditions in which water tables are low enough to create a layer of enhanced mineralization but high enough to intrude into the rapidly conducting soil layer. Maximum fluxes occur episodically when a period of water table drawdown, which produces high soil porewater DOC concentrations, is interrupted by wet weather that elevates the water table and flushes the accumulated DOC into nearby streams. The trade-off between enhanced mineralization and increased lateral flows varies within and between seasons, creating predictable seasonal patterns in stream DOC overlain by unpredictable peaks and valleys reflecting episodic flushing events. Soil DOC concentrations are always high in the saturated, hydrologically inactive layer, but low hydrologic conductivities limit movement out of the soils. Therefore there is always a high-concentration, low-flux input from deeper soils layers that creates a base-flow concentration that is higher than non-wetland systems but lower than the seasonal peaks generated within the hydrologically active layer.

Upland soils do not typically exhibit the same threshold water table–discharge response as the wetland soils (Herendeen, 2014). This is because the relationship between precipitation, water table, and discharge is more varied in these units (Fig. 3). The well-drained upland soils also exhibit horizonation, but the organic horizon is generally thin and porous. Even in cases of deep, unsaturated organic horizons that meet the soil taxonomic criteria for a folistic epipedon, water is transmitted quickly through the fibric O horizon (US Forest Service, 1997). Moreover, the development of spodic horizons in the upland soils also supports the existence of subsurface water translocation. Thus, DOC concentrations and fluxes in upland soils are lower than in the two wetland hydropedologic units because there is less DOC in the soil solution due to the lower residence time in surface organic horizons. Upland soils also have a high soluble C sink capacity in the spodic horizon due to the formation of stable complexes with Al and Fe (McDowell and Wood, 1984). The mineral soils often overlie bedrock or till as observed in all three upland units in this study, but due to higher slope gradients, water moves more rapidly downgradient through mineral soil horizons. The transfer of DOC-laden water downgradient increases the interaction with mineral soil layers, promoting an increase in the lateral formation of stable organo-mineral complexes that reduce the flux of DOC from upland soils (Bailey et al., 2014; McDowell and Likens, 1988).

Partitioning the Landscape into Hydropedologic Units to Predict Specific Dissolved Organic Carbon Fluxes

The hydropedologic units in our study provide a set of building blocks for predicting the hydrologic export of DOC from PCTR watersheds. Most of the non-glacial terrestrial ecosystem can be classified as functional units by soil hydrology (wetland or non-wetland) and aboveground vegetation (forested or non-forested). Although it could be argued that the poor fen and forested wetlands behave similarly enough to support aggregating them into a single "wetland" unit, the utility of the hydropedologic unit approach to future flux predictions supports retaining them as separate classes. The seasonal timing, mass, and quality of litter inputs to the soil surface are markedly different between forested and non-forested land cover types, and vegetation cover is expected to respond significantly to predicted climate changes. Therefore we expect that the dynamics of the active soil surface layer will vary significantly between the two wetland types, and our ability to predict the net effect of such changes on DOC fluxes requires that the two different wetland units be maintained. The large fluvial C fluxes from these three common hydropedologic units indicate that DOC fluxes are quantitatively important components of C budgets in the PCTR. The proportion of the watershed that contained poor fens in our study watersheds varied from 9 to 63% and the forested wetlands varied from 14 to 32%. Although these areas may be a small percentage of the total landscape, our results show that these hydropedologic units have very high specific DOC fluxes and thus are important for the hydrologic mobilization of DOC at the watershed scale. Upland soils have lower DOC fluxes but tend to dominate in terms of area and thus generate high total DOC fluxes relative to other forest types. The two wetland hydropedologic units represented in our sampling comprise >75% of the wetland types in the Tongass National Forest, which in turn covers >80% of the land ownership in the Alaskan PCTR (Table 1). By weighting watershed DOC export estimates by the relative proportion of these distinct units across the landscape, our data will allow more precise modeling of DOC export in the region. The PCTR is comprised of approximately 78% uplands, 12% forested wetlands, and 9% poor fens. The variation in unit distribution within our study catchments resulted in integrated fluxes from 10.5 to 29.9 g C m^{-2} yr^{-1} from the three hydropedologic types (Table 3). Applying our specific DOC export values to an area-weighted average, we estimate that roughly 14.0 ± 4.5 g C m^{-2} yr^{-1} is exported from the landscape on average. This equates to 960,000 Mg (0.9 Tg; range of 0.7–1.2 Tg) of DOC exported via lateral transfer from the land to water in an area equivalent to 6.8 Mha in the Alaskan PCTR.

Previous research on two watersheds near Ketchikan, AK, estimated annual DOC flux from concentration and discharge measurement (Sugai and Burrell, 1984). These estimates do not provide a means to extrapolate the flux of DOC to other watersheds but do provide a comparative estimate for our modeled watershed flux. The estimate of DOC export was 13.3 g C m^{-2} yr^{-1} from the low-gradient wetland-dominated system in the Wilson River and 7.9 g C m^{-2} yr^{-1} in the upland-dominated Blossom River drainage. Our average watershed estimate of 14.0 g C m^{-2} yr^{-1} is equivalent to the wetland-dominated system in the Wilson River watershed. The higher average value in our estimate is probably due to our inclusion of concentrations from high-flow events in our model calibration. In both cases, these estimates confirm that large quantities of DOC are exported from streams and rivers in the region. Understanding the spatial distribution of hydropedologic units and their seasonal behavior is a critical advance in understanding existing flows of DOC from small catchments. The periods of critical loading and peak export are important for the estimation of maximum export loads to streams, as well as modeling potential future changes in DOC export.

CONCLUSIONS

Our results provide evidence that hydropedologic units provide a good approximation for determining DOC export from watersheds in the PCTR. The timing of soil hydrologic fluctuations combined with seasonal soil temperature patterns largely explains the quantities of DOC exported from the hydropedologic units in the late summer and early fall, thus making these simple physical parameters effective predictors of catchment DOC flux. Our estimates from the hydropedologic units provide a means to quantify DOC fluxes from watersheds in the PCTR and provide a framework to evaluate the impact of climate change on watershed and regional DOC fluxes.

ACKNOWLEDGMENTS

We would like to thank Erik Norberg, Jacob Berkowitz, Nick Bonzey, Mark Lukey, and Adelaide Johnson for field and laboratory assistance. This research was partially funded by the USDA National Research Initiative, Grant no. 2005-35102-16289.

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