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The character and bioactivity of dissolved organic matter at thaw and in the spring runoff waters of the arctic tundra north slope, Alaska

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Abstract. The brief spring thaw period in the arctic is an important time when carbon is transferred from terrestrial to aquatic systems as melting snow and soil waters run off into the streams, lakes, and ocean. Measurements were made of the quantity and quality of dissolved organic carbon (DOC) in thawing soil and runoff waters in the foothills region of the Kuparuk River basin of arctic Alaska, during the thaw of May 1996. Incubations were performed using DOC and soil cores at the time of thaw from the surface layers of two major tundra types of the region, nonacidic and acidic tundra. Results indicated that there are major changes in both the quantity and quality of DOC as soil waters thaw and move to the streams and lakes. DOC concentrations were found to be reduced up to 90% as soil waters thawed and became free-flowing soil waters with leachates from thawed soil cores averaging 116 mg DOC/L at thaw and soil waters averaging 20 mg DOC/L. Stream and inlet to Toolik Lake DOC concentrations averaged 12 and 10 mg DOC/L respectively indicating further dilution of DOC. Quality differences elucidated by XAD-8/4 resin fractionation of DOC were observed for waters at various points in the ecosystem. The hydrophilic neutral fraction (HIN) accounted for 71% of the DOC in waters of thawing soil cores, but was only 23% in flowing waters of soils, and 9-20% in stream waters. A 14 day 4°C incubation of DOC from thawing soil core waters reduced DOC an average of 39%, with 80% of that reduction occurring in the HIN fraction. Soil waters and stream waters were similar in DOC fraction composition, and fulvic acid fractions were dominant. Initial 14 day DOC respiration rates with high HIN waters were 10 mg CO_2-C/g DOC/d, and reduced to 1.2-1.7 mg CO_2-C/g DOC/d after 34 days incubation. Respiration rates of thawed cores ranged from 0.12 to 0.06 and 0.03 mg CO_2-C/g C/d for nonacidic and acidic cores, respectively.

1. Introduction

The predictions of global climate models and observations of the present regional climate trends point to relatively strong climate warming for the northern latitudes [*Kahl et al.*, 1993]. How the terrestrial part of the arctic system will respond to this warming and its role in this change is the subject of a coordinated series of projects within the National Science Foundation (NSF) Arctic System Science Program [*Weller et al.*, 1995]. These projects have measured both gaseous and hydrologic fluxes of carbon from arctic tundra. Hydrologic fluxes transfer large quantities of carbon from land to aquatic systems [*Peterson et al.*, 1986; *Kling et al.*, 1991]. Spring runoff of snow and soil meltwaters [*Kane et al.*, 1992] is thought to transfer substantial amounts of C and N in tundra systems [*Hobbie and Chapin,* 1996].

In temperate systems, dissolved organic matter (DOM) moves with water from the soil upper organic detritus layer through the mineral layers to the water table. During movement, DOM decomposes, interacts with metals, and often precipitates at depth in ferro- and alumino-organic mineral coatings [*Wolt*, 1994]. During movement, the quality of DOM entering the aquatic system changes reflecting the character of mineral soils in the watershed [*Nelson et al.*, 1991]. In temperate regions, as much as 95% of the DOM entering the soil profile may be removed from water prior to its entering streams [*Qualls and Haines*, 1992].

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Typically, the DOM of arctic systems is carried in a slightly different pathway, which is controlled by the seasonal progression of thaw depth, the permafrost table, and the hydraulic conductivity associated with the boundaries between organic and mineral layers [*Hinzman et al.*, 1993]. DOM movement is constrained vertically, resulting in restriction of DOM movement to the upper organic layer during most of the summer season. There is thus little interaction of DOM with soil mineral layers except for a brief period in the later part of the summer season. Interaction of DOM with metals and subsequent precipitation on mineral surfaces is limited, resulting in a greater potential for DOM to leave the soil and enter the aquatic system.

The quantity of DOM leaving tundra on the foothills and entering streams and lakes is a function of the spring thaw and the flushing action of storm events throughout the summer season [*Whalen and Cornwell*, 1985; *Peterson et al.*, 1986]. In coastal plain and wetland complexes, movement of water is controlled by snow melt and seasonal active layer thaw [*Hobbie*, 1980; *Rovansek et al.*, 1996]. Typically, the largest amount of DOM enters surface waters during spring thaw.

Substrate quality differences have been investigated in DOM of both water and soil. In temperate zone systems, composition of DOM is key to its bioavailability. *Qualls and Haines* [1992] found that microbial activity changed DOM composition as it moved through the ecosystem from vegetation throughfall to stream water flow. Various microbes present in natural systems are able to use the DOM of soils, streams, and lakes [*Tranvik and Hoefle*, 1987; *Meyer et al.*, 1987].

Studies in cold regions have identified unique factors that affect the quality and quantity of soil DOM. Soil freezing and freeze-thaw cycles serve to increase bioactive DOM in soils as a result of the cell lysis in the soil microbial biomass [*Schimel and Clein*, 1996]. Studies of thawing dead subantarctic plant leaves revealed that freeze damage releases up to 80% of soluble leaf carbohydrates including sucrose and trehalose within 6-8 hours after thaw [*Hurst et al.*, 1985]. The combination of thick surface soil organic layers with extreme seasonal temperature change results in a high potential for freeze-thaw release of soluble carbohydrates in tundra soils. The flushing action of rapid spring snow melt and runoff creates conditions favorable for release and transfer of large amounts of soluble carbohydrates in DOM. In fact, the DOM released during spring runoff was shown to be highly available to bacteria in Toolik Lake, arctic Alaska [*Kling*, 1995].

The objective of this study was to chemically characterize DOM present in early arctic stream runoff and soil waters and to relate this to DOM bioavailability. The study includes moist nonacidic and moist acidic tundra sites from the carbon flux study on the north slope of Alaska described by *Weller et al.* [1995].

2. Materials and Methods

2.1. Sites and Sampling

Soil sampling sites were in moist nonacidic and moist acidic tundra of the arctic Alaska foothills described in Table 1. Frozen soil cores 10 cm in length were collected from under snow-covered areas using a 2.5 cm ID hollow core drill. Eight cores were collected from each site. Each core was sealed in the barrel of a plastic 60 cm^3 syringe immediately upon removal from the ground and placed in a freezer for storage. Triplicate soil water samples were collected in bottles from flowing free water of the upper 10 cm of soil in thawed areas of the same sites.

Water samples were collected during the early stages of spring thaw (May 14-17, 1996) from sites listed in Table 1. Samples taken daily from the inlet stream to Toolik Lake were concentrated by reverse osmosis, and each represents about 500 L of stream water. Stream and water track samples were collected in 2 L bottles by submersion in the flowing water. Water considered to be winter resident was sampled from Toolik Lake by pumping from a 5 m depth through a hole in the ice drilled over deep water at the southwestern end of the lake. A water sample was taken from the initial flow of the stream draining the Acidic-2 soil sampling site. This sample was from under the snow about 1 km above the stream's inlet to Toolik Lake. The other stream water samples were taken from flow just before the streams crossed the Dalton Highway. All water samples were stored on ice until analysis.

2.2. Fractionation of DOC

Water samples were filtered through a 0.45 µm polysulfanone filter, and the dissolved organic carbon (DOC) fractionated using the tandem XAD8-XAD4 resin procedure of *Malcolm* [1992] with modifications described by *Boerschke et al.* [1996]. This procedure results in the separation of DOM into six fractions (humic acid (HA), fulvic acid (FA), hydrophobic neutrals (HON), low molecular weight acids (LMA), low molecular weight neutrals (LMN) or combined low molecular weight acids and neutrals (LMAN), and hydrophilic neutrals (HIN)) based on sorption to and desorption from the resins. Frozen soil cores were thawed to 4° C and leached with 4 core volumes of deionized water, all within an 8 hour period. The leachates from the eight cores at each site were paired and mixed to make four samples for each site. Each leachate sample was then split, with 200 mL placed in amber 950 mL septa jars for incubation and about 200 mL for DOC fractionation described above. The DOC concentration of samples was determined as mg C/L on an OI model 700 total organic carbon (TOC) analyzer using persulfate oxidation, IR detection, potassium biphthalate standards, and deionized water blanks.

2.3. Incubation of DOC and Soil Cores

Filtered (0.45 µm) water leachates from the thawed cores (Nonacidic site, Acidic-1, and Acidic-2 tundra sites) were inoculated with 0.5 mL of inoculum prepared from mixing equal parts of the unfiltered leachate from all sites. Blanks contained deionized water and inoculum only. Inoculated leachates were sealed in the septum jars described above. The four replicate leachates from each site were incubated at 4° C for 14 days, venting as necessary to keep carbon dioxide levels below 2% in the jar head space. The carbon dioxide evolved from the leachates was measured in the jar head space at 5, 9, and 14 days using a Perkin-Elmer model 8500 gas chromatograph fitted with a chromosorb 102 column, methanizer, and flame ionization detector. At the end of the 14 day incubation period the leachates were filtered and fractionated as above.

The leached cores were incubated in sealed amber septa jars for 35 days, venting as necessary to keep carbon dioxide levels below 2% in the jar head space. The carbon dioxide evolved from the cores was measured as above in the jar head space at 6,

Table 1. Characteristics of Sampling Sites Located in the Kuparuk and Sagavanirktok River Basins on the Central North Slope of Alaska

Soil Sites	Land Cover Class[a] Soil Classification[b]	Microrelief Landform Vegetation[c] Dominant Plants	Soil pH
Nonacidic (Sagwon LAII flux site 95-3)[d]	Moist nonacidic tundra Loamy, mixed Ruptic-Histic Molliturbel	Nonsorted circles Ridge top Forbes Carex bigelowii Dryus integrifolia	7.3
Acidic-1 (Sagwon LAII flux site 95-4)	Moist acidic tundra Fine-loamy, mixed Ruptic-Histic Aquaturbel	Tussock tundra Ridge top Shrub/Moss Betula nana Eriophorum vaginatum Sphagnum	4.6
Acidic-2 (Toolik Lk. LAII flux site 95-6)	Moist acidic tundra Loamy-mixed Ruptic-Histic Aquaturbel	Nonsorted circles Moraine, Midslope Shrub/Sedge Betula nana Carex bigelowii Sphagnum	4.6

Waters	Site Description - Location	Water pH
Toolik, water track	Streamlet draining Acidic-2 - (above)	4.5
Toolik Lk, Inlet	Whalen and Cornwell [1985] - Inlet 1	7.2
Toolik Lk, -5 m	Whalen and Cornwell [1985] - about 700 m from Inlet 1	6.3
Happy V.	Dalton Highway mile 338 - stream crossing	5.8
Dan Crk.	Dalton Highway mile 331 - stream crossing	6.2
DH Mi. 321	Dalton Highway mile 321 - stream crossing	4.9
Imnavait Crk	Oswood et al. [1996] - Dalton Highway mile 290.5	5.5
Kuparuk R.	Peterson et al. [1986] - Dalton Highway mile 290	4.8

[a] *Auerbach and Walker* [1995].
[b] *Soil Survey Staff* [1998].
[c] *Walker et al.* [1994].
[d] NSF, LAII-carbon flux study 1995, site number [*Michaelson et al.*, 1996].

9, 19, 26, and 35 days. At the end of the incubation period, the cores were leached again, the leached DOC incubated, and CO_2 evolution monitored as above.

3. Results and Discussion

3.1. Dissolved Organic Carbon

The DOC concentrations of soil waters for the Nonacidic and Acidic-1 (northernmost) sites were 50% lower at 12 and 15 mg C/L than the Acidic-2 southern foothills site at 34 mg C/L (Table 2). This difference could result from a combination of factors such as differences in the degree and timing of thaw between the two local areas and vegetation differences between sites. Compared to the more northern Nonacidic and Acidic-1 sites, the Acidic-2 site was thawed earlier and to a greater depth on the sampling date. Frost depth at sampling was 5-10 cm for the Acidic-2 sampling location as compared to 3-5 cm at the Nonacidic and Acidic-1 sites. Dilution of DOC at the shallow-thaw site relative to the deeper-thaw site could result from decreased access to soil water and an increased contribution of snow meltwater.

The thaw waters leached from the frozen soil cores were from 3 to 10 times higher in DOC (113-117 mg C/L) than the soil waters (SW) from the thawed areas (12-34 mg C/L) of the same site (Table 2). The DOC values for SW were similar to those (range 7-24 mg C/L) reported by *Kling* [1995] for the Acidic-2 site and were in the same range as those found for the Imnavait watershed [*Everett et al.,* 1996]. Leachate DOC however, was higher than any seasonal flow reported for the Imnavait stream. Midseason DOC of soil water leachates reported by *Michaelson et al.* [1997] ranged from 4 to 11 mg C/L which tended to be lower than those of the thaw leachates and comparable to the SW of this study. Thaw leachate DOC levels appear to be higher than SW during both early and midseason. A wider range of sampling would be necessary to see if this relationship holds over other tundra types on the landscape as many factors can influence solution concentration. A threefold reduction in DOC was observed (Table 2) when going from the leachate of melting cores to the SW. This could be largely due to the dilution effects of the melting snowpack. Monitoring over a narrower time period during spring runoff would be necessary to determine the impact of dilution versus biological and sorption or precipitation effects.

Table 2. Dissolved Organic Carbon of Study Soil Water Samples (Free Flowing in Soil), Stream flow, and Toolik Lake (Winter Resident Lake and Inlet to Lake Waters) Filtered Through 0.45 μm Pore Size Filters

Study Site		Collection Date	Soil Water, mg C/L	Leachate From Thawed Soil Core, mg C/L
Nonacidic tundra		May 15,1996	12 (2)[a]	117 (26)
Acidic 1		May 15,1996	15 (4)	113 (17)
Acidic 2		May 16,1996	34 (7)	117 (24)
Mean			20 (12)	116 (21)
			Stream Flow, mg C/L	
Happy Valley Crk.	Mi. 338	May 15, 1996	9 (2)	
Dan Crk.	Mi. 331	May 15,1996	6 (2)	
Dalton Hwy. Crk.	Mi. 321	May 15,1996	11 (2)	
Imnavait Crk.	Mi. 291	May 15,1996	8 (2)	
Kuparuk River	Mi. 290	May 15,1996	10 (2)	
Acidic 2 (water track)		May 16,1996	30 (5)	
Mean			12 (9)	
			Toolik Lake, mg C/L	
Resident Lake (-5 m depth)		May 14,1996	5	
Inlet to Lake		May 14,1996	15	
Inlet to Lake		May 15,1996	15	
Inlet to Lake		May 16,1996	7	
Inlet to Lake		May 17,1996	9	
Mean			10 (5)	

[a] Standard deviation is given in parentheses. The F-test was significant ($p < 0.01$) for a one-way ANOVA that included all groups of DOC (soil water, thawed soil leachate, streamflow, and Toolik Lake water), but not significant when the thawed soil leachate was not included.

The DOC of Toolik inlet water (7-15 mg C/L, Table 2) was in the same range as other streamflow DOC concentrations. The trend of decreasing DOC of inlet flow with time could be due in large part to dilution of DOC with snow meltwaters as the melt progressed because flow was increasing during our sampling (May 14-17) and reached a maximum on May 24, 1996 [see also *Peterson et al.*, 1986; *Oswood et al.*, 1996]. Resident lake water had the lowest DOC concentrations, but was within the range found by *Whalen and Cornwell* [1985] in a study of Toolik Lake during the summer season.

Streamflow DOC concentrations range from 6 to 30 mg C/L (Table 2). These concentrations are within the range reported by *Oswood et al.* [1996] for the early season discharge of Imnavait Creek. They reported a rapid decline in DOC (from about 30 to 8 mg C/L) over a 2 day period in May during the initial stages of thaw. The range in DOC found for the streams during thaw will

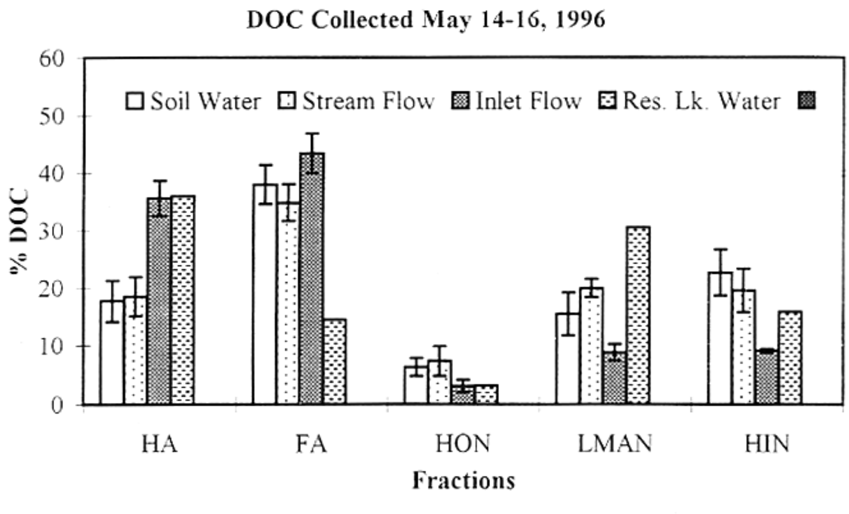

Figure 1. Fraction percentages of DOC for the soil water, streamflow,and Toolik Lake (HA, humic acid; FA, fulvic acid; HON, hydophobic neutrals; LMAN, low molecular weight acids and neutrals; and HIN, hydrophilic neutrals; see Table 1 for site characteristics). Error bars are one standard deviation above and below the mean for the three soil waters, six streamflows, and three replicate inlet to Toolik Lake samples, all taken on May 15, 1996. The resident Toolik Lake water sample is a single 200 L sample.

be influenced by many location factors such as vegetation and soils and factors such as time, temperature, and available water relating to stages of thaw progression. For arctic stream surface waters the flushing action of thaw and storm events is well known to directly affect stream DOC.

3.2. Characterization of DOC

The DOC of SW (Figure 1) was dominated by the fulvic acid (FA) fraction, which accounted for an average of 38% of the carbon. These results are similar to those reported for soil water leachate in a study of Prudhoe Bay and Toolik Lake soil [*Michaelson et al.,* 1997]. That study reported the DOC of leachate from the surface soil horizons collected in July to be dominated by FA, averaging 37% of the DOC.

Characterization data for DOC of streamflow waters were remarkably similar to those for the SW (Figure 1). The FA fraction dominated streamflow DOC in nearly the same proportion as for SW. Other fractions were also very similar in distribution to those for the SW, with the HA, LMAN, and HIN about evenly distributed, and the HON lowest in proportion. In comparing these results to values given by *Malcolm* [1985] for U.S. surface waters, the HA and HIN fractions are each almost 4 times higher in these arctic stream waters than the average for U.S. surface waters.

The distribution of DOC fractions in the inlet flow to Toolik Lake (Figure 1) was distinct from the SW and streamflow DOC. The HA and FA fractions occurred in nearly equal proportions and together accounted for about 70% of the DOC. The LMAN and HIN also occurred in nearly equal proportions but at lower levels (about 9 % of DOC) compared to SW and streamflow DOC, where averages ranged between 15 and 23% DOC. The distribution of DOC fractions in resident water of Toolik Lake (Figure 1) was also distinct from all other water samples. The HA and LMAN fractions were dominant and in nearly the same proportion accounting for over 60% of the DOC. The FA and HIN fractions were essentially equal at 15-16% of the DOC each, with HON being the smallest fraction.

The character of thaw leachate DOC from soil cores was very high in HIN, averaging 71% of DOC (from data in Figure 2), compared with other waters ranging from 9 to 23% (Figure 1). For this reduction to occur, there must be processes occurring between the onset of thaw and the subsequent runoff of waters from the tundra to the streams. These processes could include sorption, precipitation, flocculation, and biological degradation.

Another clear trend in the DOC fractionation data is the similarity in soil waters and stream waters (first two bars in Figure 1). As discussed above, the range in DOC concentration of SW and streamflow was overlapping, with the range for the SW tending to extend higher and the streamflow range lower than the mean of the two water types. These data suggest that there is little difference in DOC quality detectable by fraction distributions between SW and streamflow at this early point in the spring thaw season. The similarity may be unique to the early season flow, as *Michaelson et al.* [1997] reported distinct soil leachate DOC character differences for midseason for both ecosystem type and depth within the soil profile. For early spring, the flushing of thawed upper soil and dilution by snowmelt appear to dominate over processes that would be expected to change the quality of DOC, such as selective absorption or biological action.

The proportions of DOC fractions for the inlet waters to Toolik are different from SW and streamflow (Figure 1).

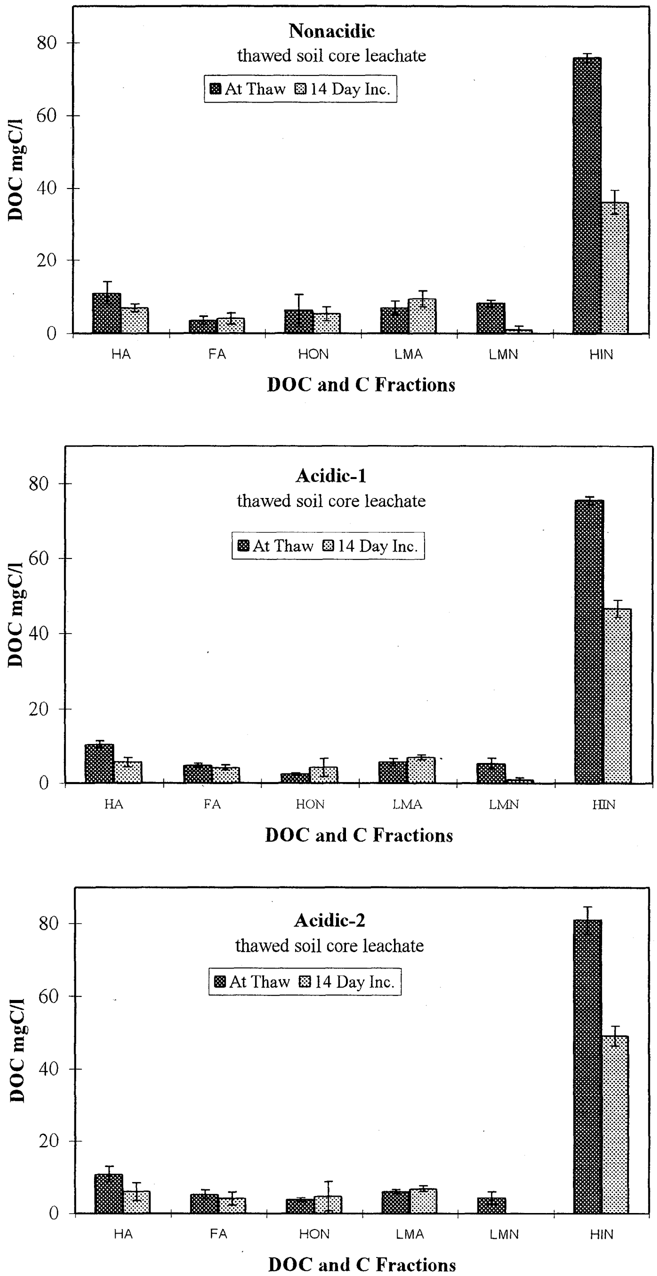

Figure 2. Dissolved organic C (DOC) and amounts of DOC occurring in fractions of soil core leachate at thaw and after incubation.(HA, humic acid; FA, fulvic acid; HON, hydophobic neutrals; LMA, low molecular weight acids; LMN, low molecular weight neutrals; and HIN, hydrophilic neutrals). Error bars represent one standard deviation unit either side of the mean.

Limitations of this study do not allow us to isolate the specific reason or reasons for this difference. There are at least two possible factors that could be at work alone or in combination to contribute to this difference in inlet flow composition. First, Toolik inlet is a much larger stream than the other streams sampled, and so the residence time of water may be sufficient to allow in-stream processing of water coming from the soils and smaller tributaries. Second, Toolik inlet flows through a series of lakes higher in the catchment, and some combination of this lake water with the soil and tributary water may interact to produce the observed DOC fractions of the inlet water. The sample of resident lake water (Figure 1) was similar in content of the more biologically stable higher molecular weight HA fraction and the HON fraction, to inlet waters but different in all other fractions.

3.3. DOC Character at Thaw and Effects of Bioactivity

The DOC fractions found in the thawed-core water leachates (Figure 2, shaded bars) are distinctly different from those of other waters in Figure 1. The HIN fraction was dominant for all three sites, accounting for 68% of total DOC at Nonacidic, 72% Acidic-1, and 81% at the Acidic-2 sites. The next highest DOC fraction was the HA, averaging about 10% DOC. High amounts of HIN at thaw were largely responsible for the high DOC values listed in Table 2 for the thawed soil leachate. Although no studies involving fractionation characterization and freeze-thaw effects were found in the literature, it has been found that freeze-thaw cycling in soils results in respiratory bursts of carbon dioxide. The bursts are presumably due to rapid use of substrates released upon lysis of microbial and plant tissue cells [*Skogland et al.*, 1988; *Schimel and Clein*, 1996]. These freeze-thaw processes can cause the release of carbohydrates including sugars [*Hurst et al.*, 1985]. In the resin procedure used here, soluble cell components such as organic acids and neutrals of 12 carbons or less, and mono and disaccharides released from live tissues, would be present in the HIN fraction [*Malcolm,* 1992]. The HIN content of DOC from the frozen active layer (before seasonal thaw) and the upper permafrost upon thawing is known to range from 46 to 75% of total DOC in thaw leachate. However, the DOC of midseason samples ranges from 13 to 22% HIN [C. L. Ping, unpublished data 1998; *Michaelson et al.*, 1997].

Incubation of soil leachate DOC for 14 days resulted in an overall reduction in DOC of 46%, 34%, and 36% for the thaw leachates of the Nonacidic, Acidic-1, and Acidic-2 sites respectively (Figure 2). The HIN fraction was reduced most dramatically during incubation for each site and accounted for about 80% of the DOC loss on incubation. The HA and LMN fractions were also reduced during incubation with only slight changes in the other fractions. *Meyer et al.* [1987], using different methods and river DOC, found similar results. They found that both high and low molecular weight fractions were biologically active, with activity in the high molecular weight fraction due to inclusion of low molecular weight compounds complexed with the high molecular weight fraction. In the procedure used here, uncomplexed low molecular weight polysaccharide DOC would be fractionated into the HIN fraction and LMN [*Boerschke et al.*, 1996]. The HIN and LMN fractions incubated in isolation by *Dia et al.* [1998] evolved 2.8 and 1.7 times as much CO_2-C per unit C in the fraction as the next highest fraction (HA). This high availability to microorganisms is consistent with our results. Our methods did not allow us to determine the relative amounts of DOC loss due to incorporation into microbial biomass, conversion to CO_2 by microbes, or losses due to chemical flocculation or adsorption from solution. We must assume that all these processes occurred, since our measurements did not allow us to separate processes. Results of other studies suggest that the relatively high losses of DOC in the HIN fraction are microbial. For example, our loss rates from ~116 to ~65 mg C/L DOC in 14 days (Figure 2) are higher than rates of bacterial use measured during experimental DOC enrichments in marine environments [*Fry et al.*, 1996] and in Toolik Lake [*Kling*, 1995], but lower than measured rates for some temperate zone rivers [*Sinsabaugh et al.*, 1997]. Evidence from similar DOC incubations, including samples with a wider range of HIN concentrations, indicates that the presence of the HIN fraction in solution is highly related to CO_2-C respiration (Figure 3). Incubations of soil water from five arctic soils at equal DOC concentrations showed that CO_2 respiration rates were highly correlated to HIN content of DOC present in the permafrost and active layer soil meltwaters with $R^2 = 0.98$, $p < 0.01$ (G.J. Michaelson and C.L. Ping, unpublished data, 1998).

Incubation of DOC in leachate removed from thawing soil cores revealed no significant differences in respiration for the three sites (data not shown). These respiration rates for thaw leachates were nearly equal for all sites at 10 mg C/g DOC/ d. When considering the standard error and analysis of variance, incubations of DOC leached from cores that had been incubated for 34 days (Table 3, leachate) were not different, mainly due to large variability in the Nonacidic leachate. For the average, the Acidic-2 sample tended to be higher relative to the Acidic-1. The rate of CO_2-C evolved from the DOC of the Acidic-2 site was stable (between days 15 and 69) averaged 1.75 mg C/g DOC/d, which was 40% higher than the average rate evolved from DOC of Acidic-1, but analysis of variance (ANOVA) tests showed variability too high for statistical significance. This indicates that although the initial (0-14 day) rates of activity in the DOC from the different tundra types are high and essentially the same, longer term respiration activity is variable. With the reduced amounts of HIN after the initial (0-14 day) incubation, the initial effect of the high HIN fraction content is likely reduced along with its predominance in the DOC. As microbial activity proceeds, the relative importance of other fractions may change.

The 34 day incubation of the thawed cores indicated that the Nonacidic and Acidic-2 cores tended to evolved on the average 70% more total amount of carbon than the Acidic-1 cores (data not shown), but variability was high, and again ANOVAs showed no significant differances (Nonacidic 9.0 ±4.0, Acidic-2 8.8 ±4.3, and Acidic-1 5.1 ±1.3 mg CO_2-C/g OC). The Nonacidic cores (Table 3) respired C at an average rate of 0.12

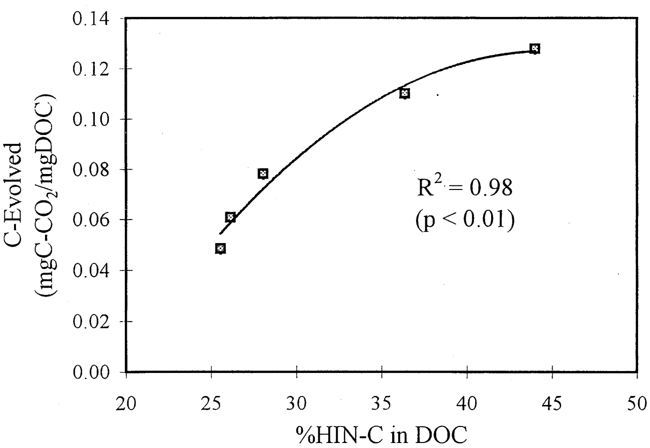

Figure 3. Initial hydrophilic neutral fraction (HIN) content and carbon evolved during the initial 10 days of incubation (4°C) for DOC released from soils upon thaw. Incubations were at equal DOC concentrations for each soil. The five soils were from the active layer and permafrost of soils at sites similar to those of Nonacidic and Acidic-1 of this study (G.J. Michaelson and C.L. Ping, unpublished data, 1998).

Table 3. Carbon Dioxide Carbon (CO_2-C) Respiration Rates for the Steady-Rate period of CO_2-C Evolution After the Initial Burst Period of the Incubation (Days 15-69 and 19-43 for Soil Leachate and Soil Core Incubations Respectively).

Soil	Nonacidic	Acidic-1	Acidic-2
Leachate (from 34-day incubated cores)	1.77 (1.06)[a]	1.24 (0.03)	1.75 (0.04)
Cores (0-10 cm)	0.12 (0.04)	0.03 (0.05)	0.06 (0.04)

[a] Numbers are average rates (mg CO_2-C/g OC/d) for replications with the standard error in parentheses. Analysis of variance (one-way ANOVA) for the individual incubation rates of each soil and soil leachate revealed no significant effect for soil leachate type on CO_2-C evolution but soil was significant ($p < 0.01$) in affecting the core incubation evolution rates.

mg C/g OC/d, which was 4 times higher than the 0.03 mg C/g C/d and twice the 0.06 mg C/g C/d rate averages observed for the Acidic-1 and Acidic-2 cores, respectively. Although the standard errors were relatively high, the ANOVA showed the effect of different soil core was significant ($p < 0.01$).

The C:N ratio of organic matter is considered to represent the relative quality of the material. The ratios were quite variable, similar to the CO_2-C respiration rates. The C:N ratios of the cores were 30 ±5, 47 ±28, and 39 ±7 for the Nonacidic, Acidic-2, and Acidic-1 cores, respectively.

4. Conclusions

During the spring thaw of tundra ecosystems, waters from soils, streams, and lakes exhibit a wide variation in DOC concentration. The highest DOC concentrations are found in the soil water at thaw with a reduction in DOC concentration as water enters water tracks, streams, and lakes. DOC concentration can be reduced by as much as 90% as waters move from soil solution at thaw to free flowing soil water as thawing progresses. Up to an additional 50% reduction in DOC concentration may occur before flowing soil waters enter streams or lakes. Analysis of DOC by fractionation indicates that a substantial change in the chemical character and quality of the DOC occurs along with concentration changes. There is a dramatic change in the character of DOC of thawed soil water, which is dominated by HIN (71% of total DOC), when compared to the flowing soil waters where FA is dominant at 38% of DOC and HIN is reduced to 23%. The composition of DOC in the stream waters which flow early in the spring either reflect the soil water composition or, as in the case of Toolik inlet waters are dominated by both HA and FA. The DOC of resident Toolik Lake water is dominated by HA and LMAN.

Changes in the character of DOC indicate that simple dilution of DOC is accompanied by processes such as selective sorption, precipitation, and microbial decomposition. The presence of high concentrations of HIN at thaw in soil water DOC is consistent with release of carbohydrates from cell lysis due to soil freezing. The reduction in HIN during incubation, correlation of HIN to respiration in incubation, and the presence of lower relative amounts of HIN in other waters is evidence for the relatively high biochemical reactivity of this fraction in ecosystems as has been found by others in the laboratory.

The initial respiration rates upon thaw for DOC of the soil waters are relatively high and essentially the same among waters from different sites, probably due to uniformly high HIN content. After a period of soil incubation there, variability remained high, with no statistical differences observed in DOC respiration among soils. Variability is probably due to DOC quality changes and differences in amount and bioactivity of other DOC fractions. Whole soil cores show significant differences in respiration also with averages having the same general trend among the soils as the leachate DOC.

Understanding the unique character and changes that occur as DOC is transferred from terrestrial to aquatic systems is key to understanding the ecosystem as a whole and the processes occurring in each part. Results here point to the unique qualities of the arctic system, especially the thawing period and the constraints that the shallow thaw depths may impose on the transfer of carbon. The DOC of this system is very important for lateral C transport as well as trace gas fluxes [*Kling et al.*, 1991] and bacterial metabolism in lakes [*Kling*, 1995]. Although the spring thaw is the major event in the arctic, measurement of a complete seasonal pattern of DOC quantity and quality would be necessary for a more clear understanding of the transfer and fate of carbon in arctic tundra over the annual cycle.

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