The Effect of Soil Drainage on Fire and Carbon Cycling in Central Alaska

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Abstract

Relatively high rates of plant production coupled with low rates of decomposition allow boreal forests to store large amounts of carbon. Fire, the main disturbance of this ecosystem, also plays a key role in regulating this biome's C storage. All three of these factors are sensitive to climate change. For this reason, it is important to understand the interactions between fire, productivity, and decomposition, as well as how these interactions vary with soil drainage.

We are currently investigating the effects of fire on soil temperature and vegetative regrowth for different soil-drainage classes. Various soil, thermal, and vegetative properties are being measured within different-age black spruce (*Picea mariana* (Mill.) BSP) stands in well-drained, moderately well drained, and poorly drained areas. While the absolute amount of organic matter lost to fire is greater at moderately well drained sites, the relative amount of organic-matter loss is greatest at well-drained sites. Loss of any organic matter profoundly affects soil temperature—differences between burned and unburned plots ranged as high as 13°C. Soil drainage also affected which species were dominant postburn. Quantifying the effect of soil drainage on such factors as depth of organic matter, soil temperature, and vegetative regrowth will aid in understanding the impact of fire on boreal-forest C storage.

Introduction

Boreal forests are conifer-dominated ecosystems with thick deposits of organic matter that generally occur between lat 45° and 70° N. One of the largest biomes in the world, these forests play an important role in the global C cycle. They contain more than 300 Gt C, of which approximately 60 percent occurs within organic soil layers and mineral-soil horizons (McGuire and others, 1997). Large amounts of carbon are stored in boreal forests as a result of the unique combination of solar illumination, temperature, and precipitation within these ecosystems (Kasischke, 2000). Long summer days allow relatively high rates of net primary production, whereas cold annual temperatures protect this carbon from decomposition. Discontinuous permafrost also underlies many of these forests. Permafrost not only influences soil temperature but also strongly affects soil drainage.

The importance of such factors as soil temperature to these ecosystems makes the boreal region sensitive to climate change (Cubasch and others, 2001). Further increases in temperature will likely degrade much of the permafrost, in turn raising soil temperatures and lowering water tables. This climate change could also affect the frequency and severity of wildfire in the boreal region. Because fire is the dominant disturbance in this region, changes in the fire-return interval and (or) fire severity can greatly affect the exchange of atmospheric and terrestrial C. Fire affects C storage of the boreal forest both directly (for example, fire emissions) and indirectly. Because most of the postburn soil surface consists of relatively unshaded, black, charred material that has a lower albedo than that of a living forest, fire tends to increase soil temperature (Viereck, 1981). Postfire soil is also subject to greater degrees of heating and cooling because the organic layers, which play an important role in soil insulation, have been removed (Viereck, 1981). Changes in soil temperature directly affect decomposition rates, vegetative regrowth, soil-moisture regimes, and rates of evaporation and transpiration.

The affect of climate change on fire may depend on soil drainage. Soil-drainage class affects such factors as fire frequency and severity (Harden and others, 2000), vegetation recovery (Viereck and others, 1983), and rates of decomposition (Flanagan and Van Cleve, 1983). Because 40 to 60 percent of Alaska consists of poorly drained soils (Meier and others, 2000), it is important to understand not only how fire affects the C storage of boreal forests, but also how this response varies with drainage type. Therefore, the U.S. Geological Survey (USGS) has undertaken a study to examine the C cycling of various drainage types within interior Alaska. The USGS is currently measuring various soil, vegetation, and thermal properties in collaboration with many other investigators and institutions. Here, we outline the format of our site establishment, report on the status of measurements (underway and planned), and provide a general synthesis of organic-layer thickness, canopy density, and temperature levels within our site matrix.

Methods

Field Sites

All field sites are in central Alaska. The first study area is in Donnelly Flats (lat 63° N., long 145° W.), about 80 mi southeast of Fairbanks near Delta Junction (fig. 1). During summer 1999, a wildfire burned more than 18,000 acres of moderately well drained and well-drained land. Plots have been established within burned areas of both of these drainage types. Several other sites near Donnelly Flats, representing different stand ages (time since last fire) and soil-drainage conditions, are also being investigated (table 1). The results presented here are from sites within the Donnelly Flats study area.

The second study area is in Tanana Flats, about 12 mi southwest of Fairbanks (lat 64° N., long 148° W., fig 1). During summer 2001, a wildfire called the Survey Line fire occurred within several poorly drained parts of the area. Plots are currently being set up within this new burn, along with two nearby stands representing different stages of ecosystem recovery (table 1).

Plot Setup

Plots at sites within the Donnelly Flats study area were set up along two transects that were arranged in an "L" formation. The purpose of this setup was to capture each site's spatial variation, as well as negate directional effects on any measurements (for example, the affect of the dominant wind direction on woody-debris orientation). Measurements are taken within plots located along or just inside these transects.

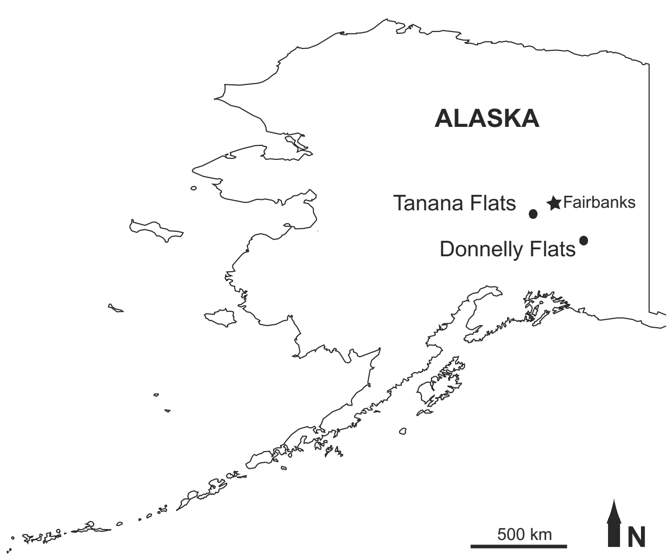

Figure 1. Sketch map of Alaska, showing locations of Donnelly Flats and Tanana Flats study areas.

These measurements include ground cover (percentage of coverage for different moss species and lichen), tree density, organic-layer/soil-horizon thickness, and temperature and moisture content at various organic-layer/mineral-soil horizons (table 2). Other measurements recorded at these sites include the C and N contents of each organic layer/soil horizon and woody-debris inventories (table 2; data not presented here). Plots, using the same format, are currently being implemented at sites in the Tanana Flats study area.

We note that all of the research discussed here is highly collaborative, with various funding institutions and scientific investigators. These partnerships are providing a more complete picture of the effects of both fire and soil drainage on the C cycle. Additional data being collected include eddy flux (Jim Randerson, California Institute of Technology); net primary production and N cycling (Michelle Mack, University of Florida); forest productivity, using remote sensing (Erik Kasischke, University of Maryland); dissolved organic C in leachate (Jason Neff, USGS); and chamber flux measurements (Ted Schuur, University of Florida).

Ground Cover and Tree Density

Ground cover (for example, moss, lichen) was digitally measured, using either 60- or 100-cm^2 area plots permanently located along our transects. First, polygons dominated by different moss species within each plot were delineated by using dyed Q-tips. These marked plots were photographed with a digital camera. At the same time, a rough sketch of each plot was made to record the relative percentage of cover for each moss species within each polygon. The digital photographs were imported into ESRI ArcGIS software, and coordinates that corresponded to each plot's borders on a 60- by 60-cm or 100- by 100-cm grid were assigned. Using a combination of ESRI ArcMap and ArcCatalog software, polygon boundaries were digitized (traced), allowing the area of each polygon to be calculated. Percentage of cover of each moss type was then averaged for the site (n=7–9 for 60-cm^2-area plots, n=13 for 100-cm^2-area plots).

Stand density was determined by using regularly spaced points placed every 30 or 40 m, depending on site, along the transect. Density of trees >3 m tall was measured by using the point-center-quarter method (Cottam and Curtis, 1956). Species, diameter at breast height, and distance from the point were recorded for the closest tree (live or dead) in each of the four quadrants (northeast, southeast, southwest, northwest) surrounding the point. Density is calculated from the formula

$$A = \left[\frac{\frac{1}{n}\left(\sum d\right)}{c} \right]^2, \qquad (1)$$

Table 1. Matrix of study areas (fig. 1) by soil-drainage class and relative time since last fire.

[Each four-character site name is followed by the name of the study area in which its located. Site in parentheses is planned]

Drainage	Relative time since burn				
	Recent	Recovering			Mature
Well drained-------	DFTB: Donnelly Flats		DF87: Donnelly Flats		DFTC: Donnelly Flats
Moderately well drained.	DFCB: Donnelly Flats	DF94: Donnelly Flats		DF56: Donnelly Flats	DFCC: Donnelly Flats
Poorly drained-----	TFSB: Tanana Flats		(TFSR: Tanana Flats)		TFSC: Tanana Flats

Table 2. Year in which measurements are occurring at each U.S. Geological Survey study site.

[Tree cover: aspen, *Populus tremuloides* (Michx.); black spruce, *Picea mariana* (Mill.) BSP. Soil measurements include horizon thickness, bulk density, C and N content, ^{13}C content, and for some sites, ^{14}C content. Letters in parentheses, chief data collector, by collaborator: K, Erik Kasischke (University of Maryland); M, Michelle Mack (University of Florida); R, Jim Randerson (California Institute of Technology). Do., ditto]

Site	Year of last burn	Tree cover	Moss cover	Soil	Suction lysimeters	Tree density/ moss cover	Net primary production	Soil moisture (continuous)	Soil temperature (continuous)
Donnelly Flats									
DFTB	1999	– – –	Feathermoss-------	2000	2000	2000	2001 (M)	1999 (R)	1999 (R)
DFCB	1999	– – –	do---------------	2000	2001	2001	2001 (M)	2000	2001
DF94	1994	Aspen------------	*Ceratodon* sp-----	2001	– –	2001	2001 (M)	– –	2000 (K)
DF87	1987	do------------	Feathermoss-------	2001	– –	2001	2001 (M)	– –	– –
DF56	1956	Black spruce----	do-------------	2001	– –	2001	2001 (M)	– –	– –
DFTC	<1900	do------------	do-------------	2000	2000	2000	2001 (M)	1999 (R)	1999 (R)
DFCC	<1900	do------------	do-------------	2000	2001	2001	2001 (M)	2001	2001
Tanana Flats									
TFSB	2001	Black spruce----	*Sphagnum* sp------	2002	– –	2003/4	2003/4	2003/4	2003/4
TFSR	1985	do------------	Feathermoss and *Sphagnum* sp.	2003/4	– –	2003/4	2003/4	2003/4	2003/4
TFSC	<1900	do------------	*Sphagnum* sp------	2003/4	– –	2003/4	2003/4	2003/4	2003/4

where A is the mean area (in square meters) per tree, d is the distance (in meters) of each tree to the point, n is the number of trees, and c is a correction factor based on the number of trees per point (1 tree, 0.50; 2 trees, 0.66; 3 trees, 0.81; 4 trees, 1.00; Cottam and Curtis, 1956). Stand density at each point (in trees per hectare), D, was calculated from the formula

$$D = \frac{1}{A} \times 10^5. \qquad (2)$$

Because A can be corrected for the number of trees per point and both live and dead trees were recorded, overall, live-tree, and dead-tree density can all be calculated. Density of trees <3 m tall were measured by using 2-m-radius plots located at each point. Generally, all live and dead trees >0.5 m tall were recorded; trees <0.5 m were measured in understory-biomass plots (data not presented here).

Organic-Layer and Mineral-Soil Characterization

Multiple plots at each site were described by dividing soil profiles into horizons containing mineral soil or one of the following five types of organic matter: live moss/litter (L), dead moss (D), fibric matter (F, similar to an Oi soil horizon; Birkeland, 1999), mesic matter (M, similar to an Oe soil horizon), or humic matter (H, similar to an Oa soil horizon). Dead-moss layers are composed of more dead-moss material than roots. The F, M, and H soil horizons contain roots and decomposing organic matter, the level of which varies by category. A small "b" was added to the horizon description for charred layers (for example, "bD" is burned dead moss). At most sites, a subset of these plots were sampled for analytical purposes. Bulk density and moisture content, which were also measured, were used in combination with nutrient-content measurements to calculate C and N storage at each site (data not presented here).

Temperature

Soil temperatures at sites in the Donnelly Flats study area were measured by using several different types of instruments. Two sites (DFCC, DFCB, fig. 4) used negative-temperature-coefficient thermistors (Alpha Sensors, Inc., No. 14A5001C2) attached to a CR10X data logger (Campbell Scientific). Because we calibrated each thermistor before it was installed, the accuracy of these instruments should be within 0.01°C. Another two sites (DFTC, DFTB, fig. 5) used 105T thermocouples (Campbell Scientific), also attached to CR10X dataloggers. Data from these instruments have, in the worst case, error rates of ±2.5°C, although error rates in the field are commonly much less. The last site (DF94; data not shown here) used HoboPro thermistors (Onset Computer Corp.), which have a slightly lower accuracy (±0.41°C).

Results and Discussion

Effects of Fire on Organic Layers

Because the forest floor comprises much of the fuel consumed during boreal fires (Stocks and Kauffman, 1997), surface organic layers are considerably changed postburn. These organic layers can be affected by a fire in one of two ways: they can be completely volatilized, or they can become charred. On average, in the Donnelly Flats study area, the well-drained site (DFTB, fig. 5; table 3) lost 7.0 cm of organic matter to the fire, whereas the moderately well drained site (DFCB, fig. 4; table 3) lost 9.2 cm. However, the preburn organic layer was significantly thicker at the wetter site. Therefore, the well-drained site lost 67 percent of its preburn organic matter whereas the moderately well drained site lost only 46 percent. As a result, the moderately well drained site both had more C combusted from the surface organic layer and retained thicker organic layers (fig. 2), which, in turn, provide better soil insulation than at the well-drained site. Those organic layers not burned during a fire play an important role in the long-term C buildup (Harden and others, 2000) because these layers eventually become reburied by moss, providing protection of their carbon from decomposition.

The thickness of organic layers varies not only with fire severity (fig. 2), but also with stand age (table 3). Although these data vary somewhat (see inset, fig. 2), a few interesting trends are noticeable. First, even 45 years after a fire (for example, site DF56; table 3), some evidence of a burn remains in the form of a recognizable char layer. In addition, not until late in the recovery process (>45 years) are dead-moss layers thick enough to be recognized. The late recovery of this layer is likely related to colonization by certain species of feathermoss (see below), which must have either higher rates of production and (or) slower rates of decomposition than early colonization species. Finally, we note that for the moderately well drained sites, the thickness of organic matter decreases

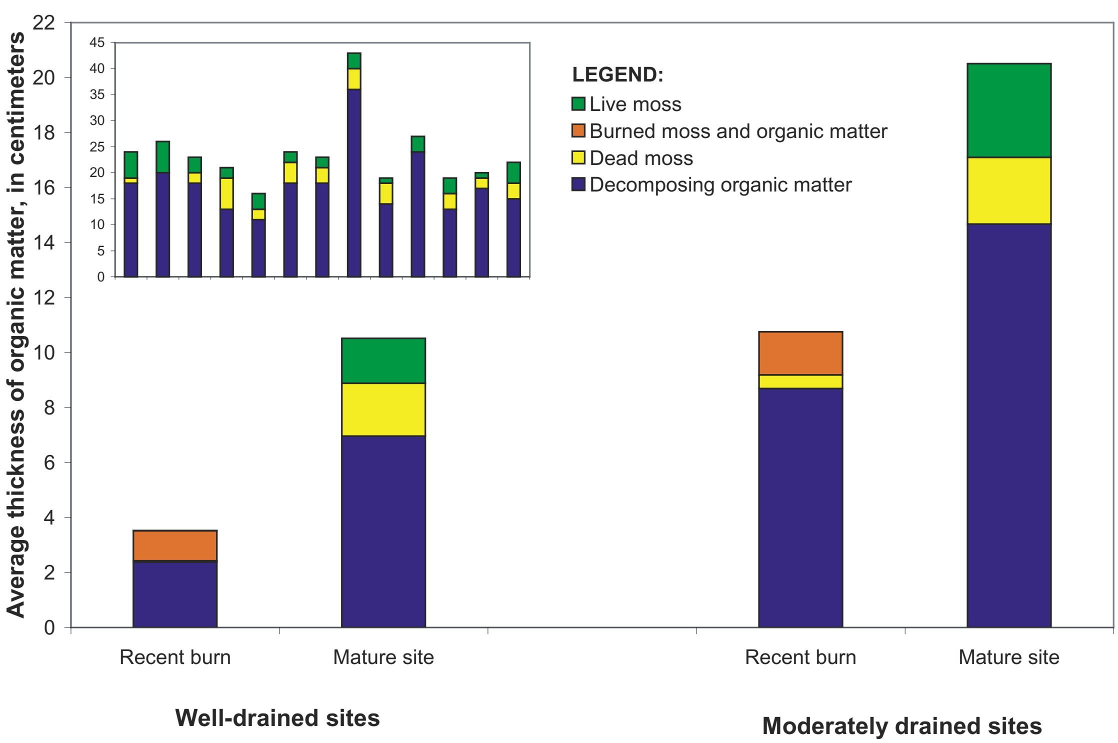

Figure 2. Bar chart comparing preburn and postburn average organic-layer thickness for sites in the Donnelly Flats study area, Alaska (fig. 1). Moderately drained sites have more organic matter, both preburn and postburn, than do well-drained sites. Inset shows variation in individual measurements of horizon thickness within mature, moderately well drained site.

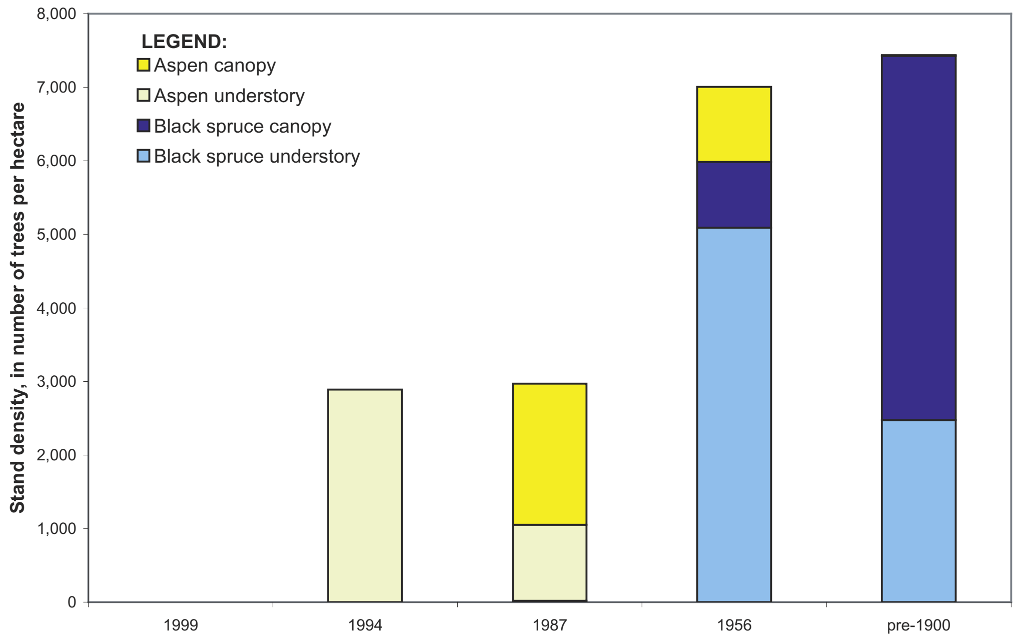

Figure 3. Stand density at sites in the Donnelly Flats study area, Alaska (fig. 1), showing how species composition of both understory (<3 m tall) and canopy (≥3 m tall) changes over time.

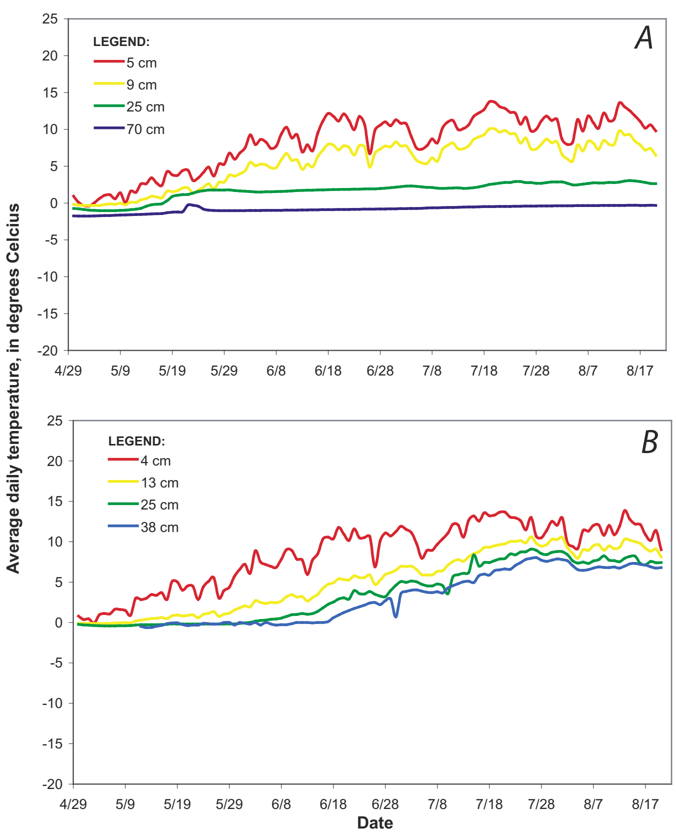

Figure 4. Average daily temperature in 2001 at various depths at moderately well drained sites (DFCB, DFCC) in the Donnelly Flats study area, Alaska (fig. 1). Lower and more even average daily temperatures are measured at mature site (*A*) than at recently burned site (*B*). Temperature probes at 25-cm depth, both in mineral soil, are most comparable.

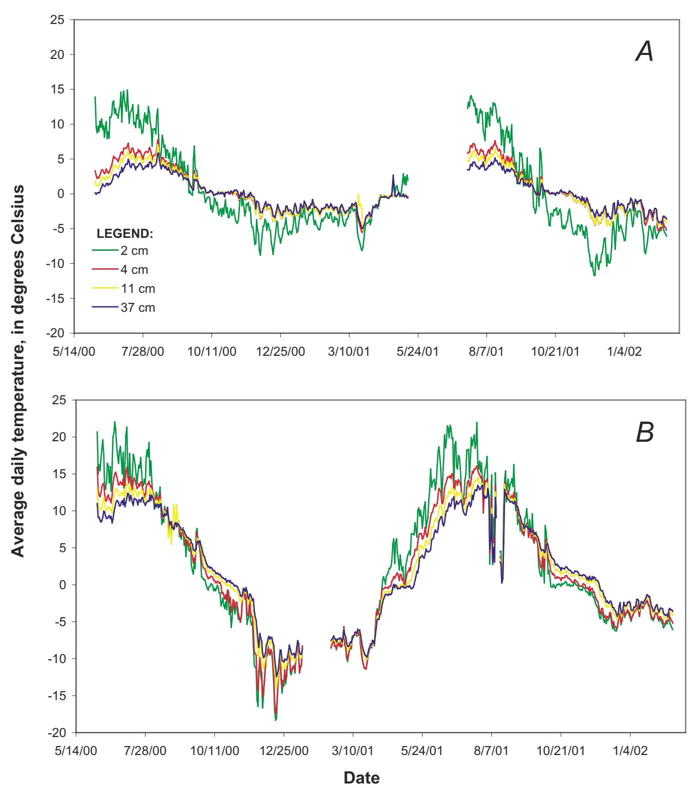

Figure 5. Average daily temperature in 2000–2 at various depths at well-drained sites (DFTB, DFTC) in the Donnelly Flats study area, Alaska (fig. 1). Seasonal amplitude is lower at mature site (*A*) than at recently burned site (*B*).

Table 3. Average thickness of organic layers at site in the Donnelly Flats study area (fig. 1), by drainage type.

[All values in centimeters. Classifications: bL, bD, bF, bM, and bH, burned moss and organic matter; D, dead moss; F, M, and H, decomposing organic matter; L, live moss. See text for definitions]

	Well-drained sites			Moderately well drained sites			
Year of burn--------------	1999	1987	pre-1900	1999	1994	1956	pre-1900
Site------------------------	DFTB	DF87	DFTC	DFCB	DF94	DF56	DFCC
Live moss----------------	0.0	0.6	1.6	0.0	1.0	3.4	2.9
Burned moss and organic matter.	1.1	3.7	.0	1.6	3.6	1.0	.0
Dead moss----------------	.0	.0	1.9	.5	.0	.0	2.4
Decomposing organic matter.	2.4	1.2	7.0	8.7	.6	1.9	14.7
Total organic matter----	3.5	5.4	10.5	10.8	5.2	6.3	20.0
Number of samples-----	20	12	26	12	11	10	14

Table 4. Differences in 2001 vegetation by drainage type and years since last fire.

[All values in percent. Study areas: DF, Donnelly Flats; TF, Tanana Flats. Average cover data are for moss, lichen, and other materials; average composition of moss cover lists the most prevalent (>5 percent) species within the moss cover. Because Tanana Flats sites were not measured until 2002, data for those sites (Xs) are based on field observations only]

	Well-drained sites			Moderately well drained sites				Poorly drained sites		
Site----------------------	DFTB	DF87	DFTC	DFCB	DF94	DF56	DFCC	TFSB	TFSR	TFSC
Average cover										
Moss (all species)------	5	58	64	5	78	56	87	– –	– –	– –
Lichen (all species)----	0	4	28	6	5	2	10	– –	– –	– –
Other (for example, soil, wood).	95	38	8	89	17	42	3	– –	– –	– –
Average composition of moss cover										
Aulacomnium sp-------	– –	– –	– –	– –	– –	78	22	– –	– –	– –
Ceratodon sp-----------	49	30	– –	9	90	– –	– –	– –	– –	– –
Dicranum sp------------	49	– –	– –	9	– –	– –	– –	– –	– –	– –
Hylocomium sp--------	– –	– –	91	– –	– –	16	54	– –	– –	– –
Pluerozium sp----------	– –	– –	– –	– –	– –	– –	10	– –	– –	– –
Polytrichum sp---------	– –	70	– –	82	10	– –	9	– –	– –	– –
Rhytidium sp-----------	– –	– –	7	– –	– –	– –	– –	– –	– –	– –
Sphagnum sp-----------	– –	– –	– –	– –	– –	– –	– –	– –	X	X
None--------------------	– –	– –	– –	– –	– –	– –	– –	X	– –	– –

drastically after a burn and recovers only very slowly (table 3). This change is likely due to the minimization of soil C inputs (net primary production) with the continuation, or increase, in C losses (decomposition).

Recovery of Vegetation

Fires within the boreal forest are generally stand replacing, meaning that little, if any, live vegetation exists immediately postburn. Therefore, both canopy and understory species go through a series of changes, known as succession. The first vegetation to colonize burned sites includes moss species, such as *Ceratodon* sp., *Dicranum* sp., and *Polytrichum* sp. (table 4). These species colonize sites quickly because they have lightweight spores or other physiologic adaptations that allow them to rapidly spread after a burn (Johnson, 1981). Which of these three species dominates the site appears to depend on drainage—the well-drained site (DFTB, table 4) is dominated by *Ceratodon* sp. and *Dicranum* sp., whereas most of the moss at the moderately well drained site (DFCB, table 4) is Polytrichum sp.

Vegetative recovery is also affected by changes in soil insulation and shading. Because no living trees remain immediately after a fire, the open stands provide an optimum environment for shade-intolerant species. One such species, aspen (*Populus tremuloides* Michx.), begins to dominate these stands within years after a fire (fig. 3). Because, on a stand level, aspen can intercept more sunlight than can black spruce (*Picea marina* (Mill.) BSP), changes in canopy cover to this tree species may affect the composition of understory and moss species. Mosses also generally do not survive the heavy litterfall below mature aspen stands (Viereck and others, 1983). Additionally, snow interception by aspen, a deciduous species, may be much less than by black spruce, resulting in warmer winter temperatures.

Over time, early-successional tree species give way to black spruce (fig. 3), which differs from aspen in that it does not provide as much canopy cover (at the stand level) as it does year-round shading. At this time, sites become dominated by late successional moss species, such *Hylocomium* sp. and *Aulacomnium* sp. (table 4; Viereck and others, 1983). Again, drainage plays a role in species prevalence; whereas most of the moss at the mature sites is *Hylocomium* sp., the moderately well drained control site (DFCC, table 4) also has significant populations of *Aulacomnium* sp. Additionally, the well-drained mature site (DFTC) has less total moss cover than the moderately well drained site (DFCC) and has significant cover by lichens (table 4). Therefore, soil drainage undoubtedly plays an important role in determining the amount and types of moss cover in both younger and older stands.

Temperature

Drainage also plays a role in soil temperature regimes. Mean late-summer mineral-soil temperatures were ~1.4°C cooler at the unburned, moderately well drained permafrost site (25-cm depth at site DFCC, fig. 4) than at the unburned, well-drained site (37-cm depth at site DFTC, fig. 5). Cooler, more stable soil temperatures at the moderately well drained site likely reflect several interrelated factors, one of which is difference in insulation by organic layers, which are thicker at the moderately well drained site. Differences also exist between the sites in water retention by both permafrost and deep mineral-soil horizons.

Fire affects soil-temperature regimes by increasing both seasonal and daily amplitudes (figs. 4, 5). Differences between burned and unburned plots ranged as high as 13°C. Two years postfire, differences in soil temperatures between burned and unburned moderately well drained sites are less pronounced than differences between burned and unburned well-drained locations (fig. 6). Thus, the thickness of insulating organic layers appears to be an important control on soil-temperature regimes in both burned and unburned stands.

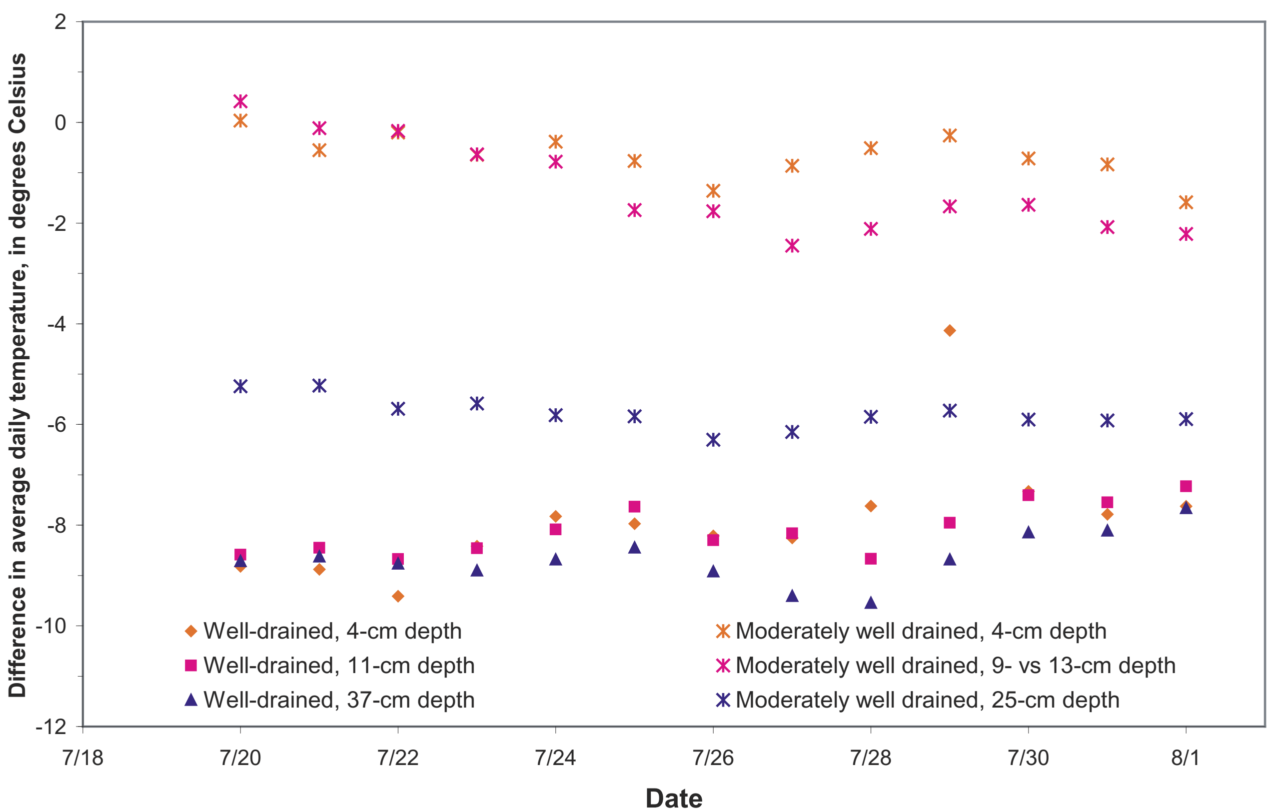

Figure 6. Difference in average daily temperature in 2001 for different soil-drainage classes at mature and burned sites in the Donnelly Flats study area, Alaska (fig. 1). Negative values indicate that temperatures are higher at burned site than at mature site. Differences are greater at well-drained than at moderately well drained site.

Conclusions

Soil drainage, and its dynamic state in the presence of permafrost, exert a major control on both ecosystem structure (for example, species occurrence) and function (for example, how species respond). Whereas fire forces major changes in the physical and chemical states of an ecosystem, soil drainage, with its control on vegetation, moderates the way ecosystems recover. The effects of soil drainage on postfire recovery are clearest during the first few years after a fire, when the vegetation responds immediately to fire severity and melting permafrost in its revegetation responses. However, soil drainage also affects long-term recovery because wetter sites regenerate moss cover of different species at different rates (table 4). The most significant effect of fire is an increase in the amplitude between summer and winter soil temperatures. Differences in temperature between burned and unburned plots at sites in the Donnelly Flats study area ranged as high as 13°C in the shallow organic layers and above 10°C for the deeper mineral-soil horizons (figs. 4, 5). O'Neill and others (2003) also observed warmer summer temperatures in burned areas.

Understanding the feedbacks between soil drainage, fire severity, and postfire revegetation will be important for predicting how fire affects boreal-forest C storage. One of our main goals is to quantify preburn and postburn organic layers, because they have been shown to strongly affect soil temperature (Viereck, 1982; O'Neill and others, 2003) and revegetation (Van Cleve and Viereck, 1984), which, in turn, affect C cycling (Zimov and others, 1999). Along with our collaborators, we are also collecting data that will allow us to quantify net primary production, nutrient inputs and losses, fire-related inputs to the soil (for example, woody debris), and C loss through decomposition (R_h). Each of these components is being examined along various drainage types so that we may better understand how fire affects the C storage in boreal forests and how this effect depends on soil drainage.

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