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FROSTFIRE: An experimental approach to predicting the climate feedbacks from the changing boreal fire regime

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[1] The FROSTFIRE research project conducted a prescribed burn of a 970 ha watershed in interior Alaska. To the best of our knowledge, this is the first experimental burn of a watershed and the most thoroughly documented prescribed fire in history. Although extensive fire research has been conducted in more temperate regions, relatively little had been done in the boreal forest and almost none in areas of discontinuous permafrost. The goal of this project was to examine the impacts of weather and vegetation on fire behavior and the resulting effects of fire on feedbacks to climate. The research was conducted in the Caribou-Poker Creeks Research Watersheds near Fairbanks, Alaska. Intensive preburn surveys quantified the preburn environment, ecology, hydrology, and fuel status of the experimental watershed. This information was compared with measurements taken during and after the fire. Although the fire was artificially ignited, the fire behavior and fire effects were similar to those of naturally occurring fires. Close collaboration among agencies and among scientists of several countries was critical to the success of the project. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1625 Global Change: Geomorphology and weathering (1824, 1886); 1699 Global Change: General or miscellaneous; *KEYWORDS:* Forest fire, permafrost, subarctic, wildfire

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1. Introduction

[2] Predicting the future role of terrestrial ecosystems in global change requires an understanding of the major terrestrial processes that affect climate. Models that incorporate these terrestrial feedbacks to climate have rapidly improved and now include temperature and moisture controls over trace gas fluxes and changes in surface properties of land-atmosphere exchange [*Kattenberg et al.*, 1996]. The success of these global models in estimating future terrestrial impacts on climate depends on our ability to include all the major processes that will have big effects on the ocean-land-atmosphere system. Those processes that remain outside of the model constitute “surprises” which the model cannot predict. Fire and other disturbances are factors that have not yet been adequately incorporated into global models [*Kittel et al.*, 2000]. Understanding the causes and consequences of fire could therefore substantially improve our understanding the role of fire-prone ecosystems in the Earth System.

[3] The boreal forest is the second most extensive terrestrial biome on earth [*Whittaker*, 1975] and has warmed more rapidly in the last 25 years than has any other biome [*Chapman and Walsh*, 1993; *Keyser et al.*, 2000; *Serreze et al.*, 2000]. This warming has led to warming and melting of permafrost [*Osterkamp and Romanovsky*, 1999] and has reduced the growth rates of dominant trees [*Barber et al.*, 2000]. It has also altered disturbance regime, including a doubling of the area burned in western North America [*Kasischke and Stocks*, 2000].

[4] Fire in the boreal forest is largely controlled by local weather and vegetation [*Ferguson et al.*, 2000] and has impacts that range from local to regional to global [*Rupp et al.*, 2000, 2001; *Goldammer and Furyaev*, 1996]. Fire return time ranges from 50–500 yr [*Lynch et al.*, 2002; *Yarie*, 1981; *Dyrness et al.*, 1986; *Kasischke et al.*, 1995b; *Kasischke and Stocks*, 2000]. This fire regime is highly variable because of its sensitivity to vegetation, topography, climate (especially short-term extreme fire-weather events), and human activities (as both a source of ignition and an agent of fire control) [*Kasischke et al.*, 1995b; *Stocks et al.*, 1996; *Dissing and Verbyla*, 2002]. Fire models that include CO_2-induced climatic warming project

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a 46% increase in fire severity rating and a 40% increase in area burned [*Van Wagner*, 1988; *Flannigan and Van Wagner*, 1991]. These projections are consistent with the doubling of the annual area burned that has occurred in the Canadian boreal forest in the last twenty years [*Kasischke and Stocks*, 2000; *Stocks et al.*, 2002]. However, the correlation between fire weather and area burned [*Flannigan and Van Wagner*, 1991] cannot be extrapolated linearly into the future. Many factors (e.g., level of protection) confound the current fire-climate correlation. Moreover, there are probably important thresholds and non-linearities in the causes and consequences of boreal fire [*Kasischke et al.*, 1995a]. Unless we improve our understanding of the causes, impacts and system responses of boreal fire, it will be difficult to develop credible models of the role of fire in the boreal forest.

2. FROSTFIRE Project

[5] The FROSTFIRE research project examined the feedbacks from boreal fire to climate in an effort to improve understanding the changing role of the boreal forest in the Earth System. The project focused on two major issues: (1) causes and consequences of fire behavior and severity and (2) effects of fire severity on feedbacks to climate.

[6] Research on fire behavior addressed the interaction of climate and vegetation by considering three causal relationships. These include (1) the relationship of weather to fuel moisture [*Sandberg et al.*, 2001], (2) fuel-bed and moisture characteristics that govern fire behavior [*Wilmore*, 2001; *Bolton et al.*, 2000], and (3) the relationship of fire behavior to fire severity [*Alvarado et al.*, 2000; *Zhuang et al.*, 2002]. We anticipate that the direct effects of regional warming in Alaska will be to increase fire severity by increasing the consumption of biomass, especially of the organic soil layer [*Ferguson et al.*, 2000]. This in turn alters patterns of succession and landscape-scale flammability [*Rupp et al.*, 2002].

[7] Research on climate feedbacks has focused on (1) trace gas fluxes, which influence global climate [*McGuire et al.*, 1995; *Kasischke et al.*, 1995a], (2) water and energy exchange, which influence regional climate [*Chapin et al.*, 2000], and (3) runoff to the oceans, which, at high latitudes, influences the strength of thermohaline circulation [*Carmack*, 2000]. Several projects have investigated fire effects on carbon and nitrogen pools and fluxes [*French et al.*, 2002; *Kasischke and Bruhwiler*, 2002; *O'Neill et al.*, 2002]. Carbon fluxes include plant-atmosphere exchanges, decomposition, hydrologic transport, and smoke [*Kim and Tanaka*, 2002; *Schuur et al.*, 2002; *Zhuang et al.*, 2002; *Petrone et al.*, 2000]. Fluxes of particulates, methane, and nitrogen gases were also examined [*Kim and Tanaka*, 2002; *French et al.*, 2002]. Fire effects on water and energy exchange were examined in terms of their effects on regional climate [*Chambers and Chapin*, 2002], runoff [*Petrone et al.*, 2000], and permafrost dynamics [*Yoshikawa et al.*, 2002]. Fire severity affected soil moisture and temperature in the short term and thaw depth and permafrost integrity in the long term [*Yoshikawa et al.*, 2002].

[8] The following hypothesized fire effects guided the design of the research (Figure 1): Fire in the boreal forest immediately affects the surface energy and water budget by drastically altering the surface albedo, roughness, infiltration rates, and moisture absorption capacity of organic soils [*Chambers and Chapin*, 2002; *Yoshikawa et al.*, 2002]. The direct losses of carbon during the fire can be large [*Kasischke and Bruhwiler*, 2002; *Ferguson et al.*, 2000] but the longer-term decomposition of carbon stored in the organic soils and in permafrost may be substantially greater [*Harden et al.*, 2000; *O'Neill et al.*, 2002]. Although fire creates a sudden, drastic change in land-cover, it is only the beginning of a long process of vegetation change, perhaps including shifts to different successional pathways (Figure 1) [*Viereck*, 1973; *Chambers and Chapin*, 2002]. In permafrost regions, these effects become part of a process of long-term (20–100 years) cumulative impacts of fire. Burn severity may largely determine immediate impacts and long-term disturbance trajectories. As transpiration decreases or ceases, soil moisture increases markedly, remaining high throughout the year. Because the insulating quality of the organic layer is removed by fire, permafrost begins to thaw near the surface and warm to greater depths [*Yoshikawa et al.*, 2002]. Within a few years, it may thaw to the point where it no longer refreezes completely every winter, creating a permanently thawed layer in the soil called a talik. After formation of a talik, soils can drain internally throughout the year, allowing soils to dry. The local ecological community adjusts to the changing soil thermal and moisture regimes. The wet soils found over shallow permafrost favor black spruce forests. After a fire

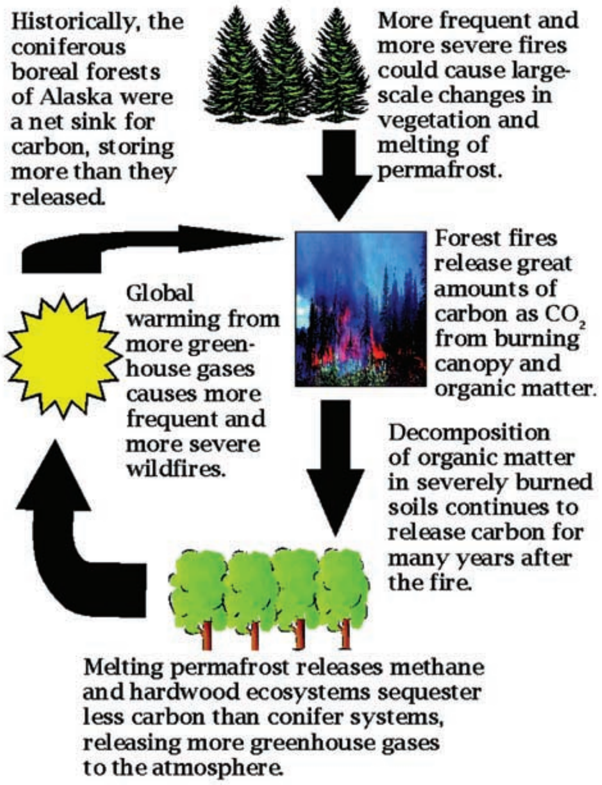

Figure 1. The occurrence of wildfires in the boreal forest has important climatic and biogeochemical consequences with large-scale global impacts.

creates a deeper permafrost table (thicker active layer), the invading tree species tend to be birch or alder. The hydrologic and thermal regime of the soil is the primary factor controlling these vegetation trajectories [*Van Cleve et al.*, 1991] and the subsequent changes in surface mass and energy fluxes.

[9] To the best of our knowledge this was the first experimental burn of a watershed and the most thoroughly documented prescribed fire in history. Ten years of preburn hydrologic data and a year of extensive preburn surveys of ecological and environmental processes throughout the watershed provided preburn information that could be compared to conditions during and after the fire. The unique combination of preburn background information and collaboration by more than fifty research projects permitted extensive sharing of complementary data sets and fostering of multidisciplinary collaboration [*Hinzman*, 2000].

[10] Prescribed burns such as FROSTFIRE provide the opportunity to observe fire behavior under prescribed conditions of fuel type and fire weather. The resulting information forms the basis for models of fire behavior and fire effects. Implementation of these fire behavior models can improve fire management through the development of more appropriate strategies for attacking and containing wildfires. An improved predictive capability becomes increasingly important as climate warms and human impacts on boreal wildlands increase. FROSTFIRE presented an opportunity for several Federal and State agencies to investigate appropriate techniques for wildfire management and to test viable strategies for prescribed burns. The broad range of vegetation types in the watershed and the range of weather conditions during the fire provided a spectrum of weather-fuel combinations that could be used to test and improve fire-behavior models. Previous prescribed fires in Canada and Russia had led to development of boreal fire behavior models, but FROSTFIRE was the first opportunity to test these models in a permafrost-dominated landscape.

[11] FROSTFIRE also provided the first opportunity to study, in a permafrost-dominated landscape, vegetation recovery and successional trajectories following fires of well-defined severity and intensity. Based on this research, land managers will be better able to predict the impacts of fire on wildlife habitat and stand regeneration. In this way prescribed fires can be used to improve wildlife and forestry resources. Prescribed burns can also decrease the threat wildfires near human habitation by decreasing the area of flammable vegetation and the fire-ignition source area.

[12] The FROSTFIRE experiment was conducted in the summer of 1999 in a 9.7 km^2 sub-basin (the C4 watershed of the Caribou-Poker Creeks Research Watershed—CPCRW) located approximately 50 km north of Fairbanks, Alaska. CPCRW is a 104 km^2 research area located in the Yukon-Tanana Uplands. It is centered about 65°10′ N latitude and 147°30′ W longitude. The Yukon-Tanana Uplands are a region of northeast-trending, round-topped ridges with gentle slopes. The elevations of these ridges range from 450 to 900 m, with rises of 150 to 500 m above the adjacent valley bottoms. The alluvial-covered valley floors are generally flat. CPCRW is a relatively pristine basin reserved for meteorological, hydrological, and ecological research. The area is underlain by discontinuous permafrost, found primarily in valley bottoms and on north-facing slopes. The average January and July temperature is $-22°C$ and 13°C respectively. The average winter snowpack yields 117 mm water equivalent and the average summer precipitation, occurring usually in late summer, is 225 mm.

[13] Approximately one third of the watershed was black spruce, a highly flammable vegetation type that has the most frequent fire return time in interior Alaska [*Dyrness et al.*, 1986]. The remainder of the watershed was dominated by deciduous forests (birch and aspen) on south-facing slopes and wet *Sphagnum*-dominated communities along the stream. Thermal analyses showed that the discontinuous permafrost is even more sporadic than expected from topographic thermal models. Surface disturbance associated with earlier forest fires in the watershed in 1890 and 1924 [*Fastie*, 2000; *Fastie et al.*, 2002] may have initiated permafrost degradation that has not yet recovered [*Yoshikawa et al.*, 2002]. This has significant implications for the long-term impact of forest fires. If, under the existing climate, the surface disturbance caused by fire initiates widespread degradation of permafrost, then substantial changes to the boreal forest ecosystems will certainly follow (Figure 2). Current research is exploring the controls over permafrost degradation and recovery following fire and the factors that might trigger permanent loss of permafrost.

3. Executing the Controlled Burn

[14] A Memorandum of Understanding was entered into by the USDA Forest Service, Pacific Northwest Research Station, the Bureau of Land Management Alaska Fire Service (AFS), the University of Alaska Fairbanks, the State of Alaska, Department of Natural Resources, Division of Land and the Division of Forestry, the State of Alaska, Department of Fish and Game and the Canadian Forestry Service. The purpose of this agreement was to provide for active cooperation while conducting FROSTFIRE research in the Caribou-Poker Creeks Research Watershed as outlined in the following sections. AFS prepared the burn plan and provided the incident commander and overhead team for the burn operation and all command and safety functions during the controlled fire.

[15] AFS conducted an environmental assessment analysis prior to ignition of the fire to determine how a prescribed fire would affect the people, environment, and historical artifacts, as contrasted with no action [*BLM Alaska Fire Service*, 1999]. They concluded that there would be no significant impacts to the human environment, if the fire was conducted as planned. AFS also prepared the FROSTFIRE Burn Plan [*Wilmore et al.*, 1998] with input from participating agencies and the public through numerous public meetings. The plan detailed the preparations and climatic conditions that must be met and maintained prior to igniting the fire. A 10 m-wide fire line was cut and all brush removed around the entire perimeter of the C4 sub-basin (970 ha) of CPCRW. This fire line was black-lined (all living and dead vegeta-

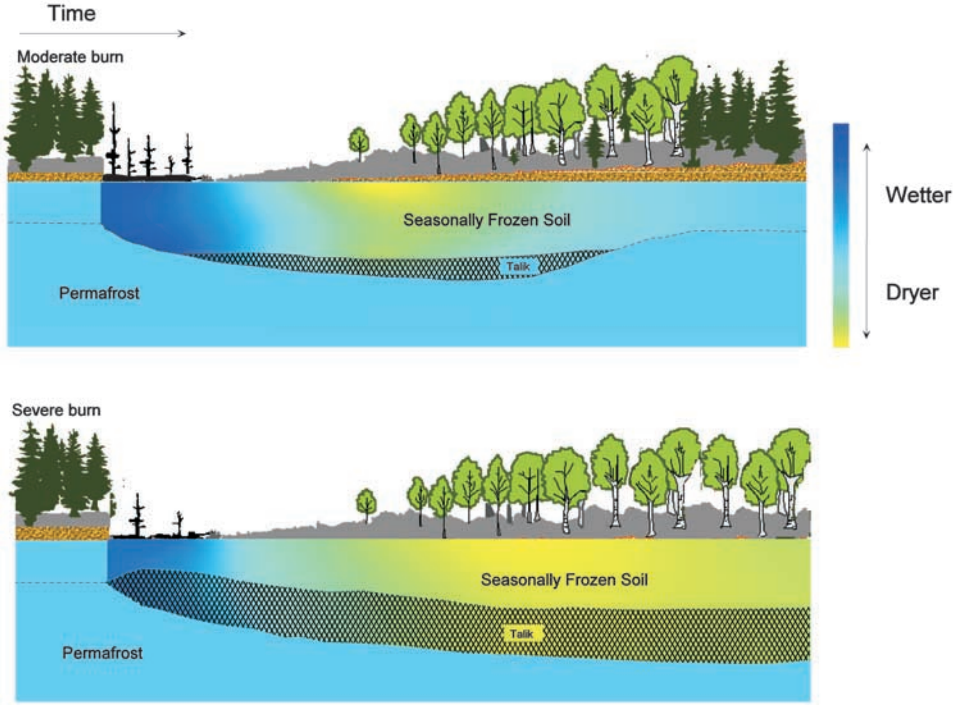

Figure 2. Hypothesized impacts of fire following a moderate (top) and severe (bottom) fires in the boreal forest.

tion burned by hand torches in small controlled fires) to 30 m prior to the fire. Large water tanks were installed and filled in strategic locations around the watershed. The entire perimeter of the watershed was plumbed with 5 cm fire hose, and pumps were installed in the watershed stream to replenish water in the tanks, if necessary. AFS crews invested over 6000 man hours preparing the fireline in the 12 months prior to ignition. During the actual fire, AFS had over 100 firefighters present to monitor and contain the fire. Additionally, two helicopters and one fixed wing aircraft were on-site transporting crews and monitoring for spot fires outside of the burn perimeter that had been ignited by sparks. One aerial tanker was loaded with fire retardant and on the ground in Fairbanks in case it was needed.

[16] A high degree of public involvement was essential to the execution of the FROSTFIRE project. Public comment was obtained repeatedly during the development of the implementation plan. Extensive discussion and widespread dissemination of the goals, objectives and methods were essential to assure the public that there were adequate safety precautions and provision for liability. Prescribed burns are a relatively new management tool in Alaska, so it was necessary to commit significant effort to public information dissemination in order to gain public confidence. A subdivision existed approximately three km southwest of the burn watershed and a highway lay just south of the watershed, so residents were justifiably concerned about the proximity of the fire. Protecting the subdivision from fire and secondary impacts such as smoke and noise and protecting the highway from smoke were among the primary goals of the burn plan. Prior to conducting the ignition of the prescribed fire, the administration of the University of Alaska agreed to accept the first line of defense for homeowners in the neighboring subdivision. The University of Alaska agreed to pay any claim immediately upon demand from subdivision residents resulting from damages associated with the experimental fire. The University administration felt it was

Table 1. Frostfire Burn Prescription With Acceptable Parameter Range

	Low	High	Desired
Temperature (°C)	17	27	21
Relative Humidity (%)	40	25	30
Live Fuel Moisture (% Spruce Needles)	125	70	85
10 m Wind Speed (kph)	5	12	8
Wind Direction	Southwest	East	Southeast
Slope (%)	0–32	0–23	0–32
FFMC[a]	88.5	92	91
DMC[b]	59	71	63
DC[c]	300	475	350
BUI[d]	77	104	87
ISI[e]	4.4	15.2	10
FWI[f]	14	42	29

The Go/No Go prescription parameters are indicated in bold; they define a proceed versus stop prescription window. The other prescription parameters serve as guides indicating when the unit is coming into prescription and indicators for meeting scientific objectives of the prescribed burn.

[a] FFMC: Fine Fuels Moisture Content, a numerical rating of moisture content of litter and other cured fine fuels in a forest stand.

[b] DMC: Duff Moisture Code, represents moisture content of loosely compacted organic (duff) layers of moderate depth.

[c] DC: Drought Code, represents moisture content of deep compact organic layers.

[d] BUI: Buildup Index, a combination of DMC and DC that represents the total amount of fuel available to the spreading fire.

[e] ISI: Initial Spread Index, a combination of wind speed and FFMC, representing fire spread rate without the influence of variable fuel quantity.

[f] FWI: Fire Weather Index, a combination of ISI and BUI that represents the intensity of a spreading fire as energy output rate per unit length of fire front, loosely defined as an estimation of potential fire danger and fire behavior in an area adjacent to a weather station where weather is recorded.

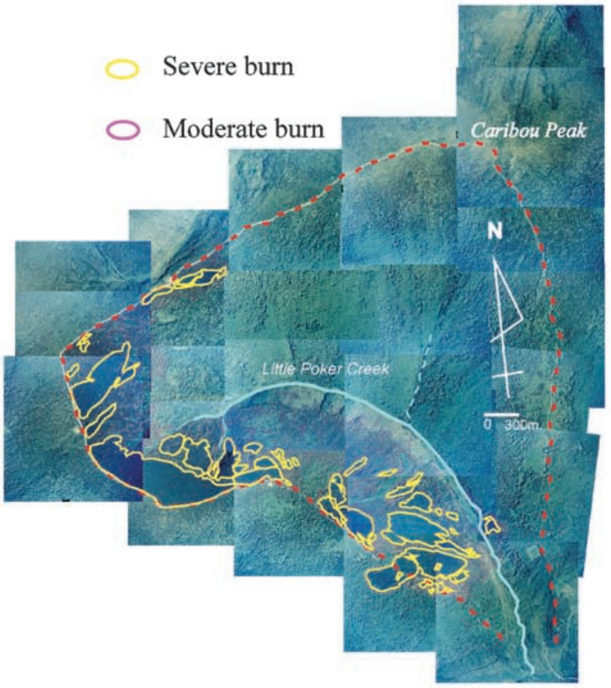

Figure 3. Mosaic of aerial photographs of the C4 subbasin in the Caribou Poker Creeks Research Watershed showing the extent and severity of the FROSTFIRE burn.

necessary and possible to accept such a stance in light of the extraordinary precautions set in place by the Alaska Fire Service prior to conducting the fire and because local residents could stop the experiment had they felt their homes were unduly endangered with little recourse for compensation. There was no collateral damage from any aspect of this project outside of the accepted perimeter.

[17] The burn plan established constraints on acceptable "fire weather". The watershed had to be dry enough to carry the fire under conditions similar to those in naturally occurring wildfires, but not so dry as to endanger AFS's control of the fire. Conditions that were dry enough for the fire were also likely to coincide with fires elsewhere in Alaska that would make fire fighters unavailable for the controlled burn. The winds were constrained to blowing to the west or northeast (away from human settlements) between 5 and 12 km/hour. Table 1 lists meteorological constraints.

[18] Aerial ignition began on July 8, 1999. The fire was ignited using a helitorch that dropped a jellied gasoline mixture from a helicopter. Some hand-firing from handheld drip torches also occurred. Rather than initiate an uncontrolled wildfire that might spread rapidly to the entire watershed, narrow strips that could be contained were ignited sequentially. Although the prescribed burn was conducted without any major incidents and was contained within the acceptable burn perimeter, a spot fire did occur outside the boundary of the fire-line, burning approximately 2.8 Ha. Some spot fires had been expected, so preparations were in place for their containment. Further ignition of the prescribed fire was halted until the spot fire was contained. Ignition only occurred on July 8, but significant burning occurred over three days with continued smoldering until July 15, 1999, when rains extinguished the last of the fire. The fire was most active during midday when relative humidity was lowest.

[19] Although this fire was artificially ignited, it behaved very much like a natural wildfire, changing from a ground fire to a crown fire at times of low humidity. As with a natural wildfire, a range of burn severities developed from irregular burning patterns (Figure 3). Only about one third of the watershed (365 Ha) burned during FROSTFIRE. The majority of the relatively flammable black spruce vegetation burned, whereas the less flammable deciduous birch and aspen stands and the wetter *Sphagnum*-dominated valley bottoms did not burn. The latter vegetation types seldom carry wildfires in Interior Alaska unless extremely dry or in cases of high winds and low relative humidities (all of which would have been outside of the allowable prescription window).

4. Conclusions

[20] The FROSTFIRE experiment was safely and successfully conducted during the summer of 1999. The BLM Alaska Fire Service burned about 365 ha of mostly black spruce. The conditions were not dry enough to burn the birch and *Sphagnum*/ spruce vegetation commonly found on the south slopes and in the valley bottoms. These burn patterns closely simulated those that occur in natural wildfires. Extensive preburn surveys and prefire documentation of environmental and ecological processes throughout the watershed enabled us to collect data before, during, and after the burn. FROSTFIRE is the most thoroughly documented fire in history, with more than fifty research projects examining a wide range of processes, including fire behavior, long and short-term impacts to ecology, hydrology, surface energy balance, and trace-gas fluxes. The extensive preburn and post-burn documentation will permit accurate and quantitative analysis on long term impacts and recovery from wildfire in the Alaskan boreal forest.

[21] **Acknowledgments.** Contributors to a large and complex project such as this are too many to mention, but all deserve a hearty thank you. The fire fighting crews of the Alaska Fire Service attacked this project with a contagious fervor. Ross Willmore and James Roessler of AFS prepared the initial burn plan. John McColgen led the fire crews during the burn. Sue Mitchell and Ellen Eberhard led the public information effort. Cathe Rich, Gregory Walker and their colleagues at the University of Alaska Poker Flats Rocket Range graciously provided logistical support and a staging and viewing area. The neighboring residents of CPCRW provided close oversight to ensure that this research was conducted safely. We are very grateful to these neighbors for allowing us to proceed with this experiment. This research was supported by the NSF TECO program (Grant No. DEB- 9728963), the NSF LTER program (Grant No. DEB-9211769), U.S. Forest Service and the Japanese New Energy and Industrial Development Organization.

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