Modeling and Monitoring Effects of Area Burned and Fire Severity on Carbon Cycling, Emissions, and Forest Health and Sustainability in Central Siberia

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ABSTRACT

Boreal forests are extremely important globally, both for their large amount of carbon storage, and as a largely unexploited source of wood fiber. Changes in land use, cover, and disturbance patterns in boreal forests can impact fire regimes and forest health, global carbon budgets, atmospheric chemistry, and wood supply. One of the key disturbance processes in these systems is fire, which affects about 12-15 million ha of closed boreal forest annually, most of it in Eurasia. This exceeds the annual area harvested or disturbed by other natural agents, such as insects.

The Russian boreal forest contains about 25% of the global terrestrial biomass, yet data on the extent and impacts of fire in these forests are scarce and often contradictory. Several recent papers indicate that the impacts on terrestrial carbon storage of fires in boreal forest regions have been vastly underestimated. Furthermore, changes in land management and land use practices, regional climate, and fire suppression capability will affect fire risk and ecosystem damage from fires in ways that are poorly understood. In changing environments, fire can be a key agent to accelerate changes toward new ecosystem conditions. Improved understanding of the landscape extent and severity of fires and of factors affecting fire behavior and intensity, effects of fire on carbon storage, air chemistry, vegetation dynamics and structure, and forest health and productivity is needed before such considerations can be adequately addressed in regional planning. To monitor effects on a landscape scale, and to provide inputs into global and regional models of carbon cycling and atmospheric chemistry requires development of validated remote-sensing-based approaches to measurement of fire areas and fire severities.

The FIRE BEAR (Fire Effects in the Boreal Eurasia Region) Project has three major goals:

- To refine and validate preliminary methods for remote-sensing-based estimates of fire areas and fire severity for forests of central Siberia, by combining ground sampling of burned areas with medium-resolution (15-120 m) and 1-km resolution satellite data.
- To develop improved data and models on effects of fire severity on fire emissions and on ecosystem damage and recovery for refining estimates of effects of fire regimes on carbon balance, greenhouse gas releases, and forest health and productivity.
- To combine experimentally-derived process data and other ground-validation data and models with the remote-sensing methods to develop regional estimates of fire areas, fire severity, and the impact of fire on carbon balance, emissions, and forest health.

Highlights of project accomplishments:

- Quantitative ground data for fire behavior in Russia.
- Field measurements of carbon consumption and emission characteristics from fires of different severities.
- Development of fire behavior and carbon-release models for fires of varying fire severity.
- Aerial observations of active wildfires and experimental 4-ha fires to assess fire severity and to monitor fire intensity.
- Refinement of remote-sensing procedures for estimating areas burned annually in Russia.
- Field validation of fire severity for wildfires observed previously from aircraft and satellites.
- ETM validation of burned area estimates from AVHRR data.
- Fire-effects studies, coupled with actual quantifiable fire behavior data, to understand ecological responses and recovery better.

Keywords: 1) Research Fields: biomass burning, carbon cycle, fire ecology, land cover classification, product validation; 2) Geographic Area/Biome: boreal forest, Russia; 3) Remote Sensing: aerial

photography, AVHRR, MODIS, LANDSAT, thermal IR; 4) Methods/scales: GIS, in-situ data, local scale, regional scale.

Questions, Goals, and Approaches

NASA ESE Scientific Questions addressed: a) What are the changes in land cover resulting from fire (monitoring of fire area and severity from aircraft and satellite)? b) What are the causes of this land cover change (how does fire severity affect land cover change)? c) What are the consequences of fire-induced land-cover change on carbon cycling and ecosystem processes?

While this research does not include a specific social science component, it does address issues critical to resource-management decision-making; much of the success of accomplishing this type of research in Russia rests as much on understanding and working with social customs/habits and administrative structures of the country and the regions as on the quality of scientific collaboration. Some 10-20% of our time was spent dealing with these necessary aspects of the work. The project supports the following research themes: Carbon: 30%; Water: 5%; Nutrients: 10%; GOFC: 40%; other (including fire behavior, ecosystem effects other than carbon, water, or nutrients): 15%.

Overall Research Goals and Approach:

- Combine ground, aircraft, and intermediate-resolution satellite data (ETM) to improve current AVHRR- and MODIS-based approaches for estimating the spatial extent of fires, and to develop and validate methods to estimate spatial patterns of burn severity for forests of the Krasnoyarsk Region.
- Use ground data from replicated experimental fires on Scotch pine sites (Fig. 1 and 2) to refine estimates of impacts of fire severity and seasonality on fire behavior, emissions, carbon storage, fuel dynamics, and ecosystem damage and recovery.
- Refine regional estimates of fire impacts on fuel dynamics, ecosystem processes, and carbon and trace gases by linking models developed from experimental data to spatial estimates of extent, intensity, and timing of fires.

Goals for Year 3 (2002):

- Conduct additional burns under varying fuel and climate conditions at the Yartsevo site and at a new site at Govorkova (Boguchany Region). Due to continuing administrative problems with the local leshoz, our original site selected in the Boguchany Region in 1988, on which plots had already been established and sampled, had to be abandoned in late 2001.Continue data analysis and begin modeling of some responses. **Completed**: Three and two experimental burns were successfully completed at Yartsevo and Govorkova, respectively.
- Acquire/build additional and replacement equipment needed for 2002 field season. **Completed**: Major addition was a LICOR instrument for measuring soil respiration.
- Complete site selection and preparation of replacement study site at Govorkova for burns in 2002. Identify an additional site with moister site conditions and develop plans for site preparation for burns to be conducted in 2003. **Completed**: A new site was located at Khreptova north of the Angara River in the Boguchany Region.
- Related to remote sensing validation efforts: A) continue aerial documentation of active wildfires using the infrared camera; B) begin analysis and ground-truthing on intermediate resolution satellite data; C) conduct ground sampling for wildfires of varying severity where infrared data was collected in 2002. **Completed**: A) Data obtained on 4 wildfires of varying intensity/severity levels; B) analysis on Landsat ETM scenes is showing that different types of disturbance have readily distinguishable signatures which can be used in classification; C) Ground sampling and helicopter overflights were carried out on 6 sites of recent and older wildfires and a range of severity levels were identified for comparison to ETM, AVHRR and experimental fire data.
- Continue development and validation of active fire and fire scar mapping with AVHRR. **Ongoing.**
- To participate at the 11th International Boreal Forest Research Association Conference held in

Krasnoyarsk, Russia. **Completed**: The following presentations were made during the conference:
  - Forest Fire in a Dry Scotch Pine Forest in Siberia: Fire Behavior and Carbon Release Estimates
  - Fire Regimes and Fuel Complexes in Pine Forests of Central Siberia
  - Emission of Particulate Matter and Gases from Forest Fires
  - Calculation of emission volume at surface fires of different intensities
- To participate at the 2002 spring American Geophysical Union (AGU) Meeting. **Completed**: The following presentations were made during the conference:
  - Emissions of trace gases from experimental fires in central Siberia
  - Mapping and prediction of fire danger by remote sensing
  - Fire frequency, distribution, and area burned in Siberia described using AVHRR-derived products
  - AVHRR-based assessment of fire patterns and area burned in Siberia
  - Assessment of a forest fire danger index for Russia using NOAA information
  - McRae invited to participate in a news conference for Session A10 (Fires, Scars, and Smoke: Observations, Impact, and Policies) detailing the FIRE BEAR Project

<u>Goals for Year 4 (2003):</u>

- Conduct additional burns under varying fuel and climate conditions at the new Khreptova site, which represented a moisture Scotch pine site compared to the previous burn sites. **Completed**: Five plots established and 2 burned.
- Acquire/build additional and replacement equipment needed for 2003 field season. **Completed**: new rate-of-spread timers obtained for fire behavior measurements.
- Continue postburn data collection on the Yartsevo and Govorkova sites; analysis to begin modeling of postfire responses. **Completed:** 2003 postfire data collected.
- Related to remote sensing validation efforts: A) conduct aerial documentation of additional active wildfires using the infrared camera; B) continue analysis and ground-truthing of intermediate resolution satellite data; C) conduct ground sampling for wildfires of varying severity where infrared data was collected in 2003. **Completed**: A) Data obtained on additional wildfires of varying intensity/severity levels; B) continued analysis on Landsat ETM scenes acquired last year is showing that different types of disturbance have readily distinguishable signatures which can be used in classification; C) ground sampling and helicopter overflights were carried out on additional sites of recent and older wildfires and a range of severity levels were identified for comparison to ETM, AVHRR and experimental fire data.
- MODIS receiving station to be installed in Krasnoyarsk. **Completed:** Station start-up in June 2003.
- Continue development and validation of active fire and fire scar mapping with AVHRR. **Ongoing.**
- Hold PI meeting in US and Canada. **Completed:** PI meeting/exchange visit held in March 2003 with Ivanova, Sukhinin, and Samsonov in Missoula, Montana. Ivanova then visited Canada to work with McRae and to make presentations to the Canadian Forest Service; Samsonov worked with Hao's group in Missoula on data and analysis techniques; Sukhinin visited NASA, Langley, and the University of Maryland to continue ongoing collaborations on remote sensing. **This exchange was funded by the Civilian Research and Development Foundation.**
- To publish initial results of the project. **Completed**: A number of papers were produced (see the publication list after the conclusions).

PROJECT ACCOMPLISHMENTS

This project has been in the planning and developmental stages since early 1996. Prior to receiving NASA funding under the 1999 NRA, site selection and establishment on three experimental areas in the Krasnoyarsk Region and preliminary remote-sensing collaboration had been completed with support from the USDA Foreign Agriculture Service ($34k) plus over $100k in contributed salaries, travel expenses, coordination meetings, site installation costs, and support of preliminary remote-sensing collaboration from the USFS, NASA, and the Canadian Forest Service. Four-hectare experimental fire plots at three sites were laid out and baseline data on soils, vegetation, and fuels collected prior to initiation of NASA funding. In addition, there were several exchange visits of Russian scientists to the US and Canada and North American scientists to Russia to discuss methods and collaboration and selection criteria of suitable sites. Collaboration with the V.N. Sukachev Institute of Forest on development of remote sensing methods for fire area and severity began in 1991. Collaboration and support of the Russian Forest Service (Krasnoyarsk Region Forestry Committee, Avialesookhrana, and local leshozes and airbases) was developed over several years of annual contacts and has been integral to the project's success.

The 2002 progress report discussed Year 2 accomplishments, including:

- Successful prescribed burns on four plots at our Yartsevo study site in 2001(two plots burned in 2000);
- Implementation of consolidated data repositories in both Russia and Canada;
- On-going investigator meetings and e-mail communications;
- Sampling of trees for developing regressions relating diameter to biomass and crown fuels;
- Continued analysis of fire IR images from 2001;
- Improvements in emissions and temperature sampling methods;
- Quantification of weather parameters, fire hazard indices, fire characteristics, fuel consumption, and carbon release from the 2000 and 2001 fires; and
- Continued work on fire detection and mapping with AVHRR.

Year 3 and 4 accomplishments:
Because of delays in implementation of some aspects of the project in 2000-2001 discussed in earlier reports, an additional field season was added, within the original project budget, in order to complete as much as possible of the planned work.

Experimental burn sites: Baseline data on plots to be burned in 2002 at Yartsevo and Govorkova sites were collected in June and July, primarily by our Russian collaborators in consultation with Douglas McRae and Deanne Shulman. McRae, John Mason, and Tom Blake (Canadian Forest Service), Deanne Shulman (USFS, Sequoia NF), and Stephen Baker (USFS-Missoula, MT) traveled to Krasnoyarsk for experimental burns in June (Boguchany Region) and July (Yartsevo). Susan Conard and Amber Soja (NASA, Langley and University of Virginia) also participated in the July burns and data collection. In July 2003, baseline data collection on plots to be burned at the Khreptova study site was done in July, primarily by our Russian collaborators in consultation with Susan Conard, Douglas McRae, Tom Blake, and Stephen Baker, who traveled to Krasnoyarsk for the experimental burns. Russian collaborators completed postburn data collection on the Yartsevo and Govorkova sites.

Field observations on wildfire sites: Russian teams collected ground validation and fire severity data on wildfires in September, 2002 and August, 2003 on sites where aerial infrared data had been obtained on active wildfires or where Landsat ETM data on fire scars were available.

Aerial infrared data from experimental fires and wildfires: In 2002 and 2003 aerial infrared data were obtained on an additional 8 experimental fires and several wildfires. These data are being used to characterize fire behavior and energy release, to model fuel consumption and carbon emissions, and to correlate with fire severity and with fire characteristics detectable on satellite imagery of fire scars and active fires.

Summary of Major Accomplishments

- **Investigators continued to exchange data and to relate their data collection to a common 25x25-m grid system, enabling excellent spatial correlation across databases.** Centralized databases are maintained by both the Canadian Forest Service (McRae) and the Sukachev Institute (Ivanova and Sukhinin). Spatial data on vegetation, fire behavior, fuels, and other characteristics are being entered into a GIS system to allow analysis across data layers. This is important for tying together all the interdisciplinary results (i.e., effects with observed quantified fire behavior).
- **Investigator meetings and communication are ongoing.** An investigator meeting was held in Krasnoyarsk in the February 2002. Planning meetings with local and federal forestry officials in Russia to discuss operational concerns, data analysis, and preparation for the summer 2002 field season were carried out by Russian collaborators. Sukhinin was also able to visit the US in late spring 2002 to take part in the AGU meeting in Washington, DC and to meet with Eric Kasischke at the University of Maryland, and some of the FIRE BEAR team (Conard, Soja, and McRae) to discuss progress and plans for the summer of 2002 on remote sensing and other aspects of the project. To save funds for the 2003 field season, the spring 2003 PI meeting was held in the US (funded by CRDF). The spring 2003 exchange visit in the US started with a week in Missoula, MT, for all participants (Conard, McRae, Hao, Baker, Ivanova, Samsonov, and Sukhinin) to discuss progress and make plans. Samsonov stayed in Missoula for an additional week to work on data and analysis methods for smoke and aerosol chemistry. Ivanova spent a week in Canada, where she and McRae presented a seminar at Canadian Forest Service headquarters in Ottawa, and then went on to Sault Ste. Marie to work on fire effects and fire behavior data. Sukhinin spent the second week meeting with NASA researchers and managers at NASA, Langley (hosted by Amber Soja and Paul Scofield). The Russian investigators returned through Washington, DC for closeout meetings with Conard and a project presentation, which was attended by people from the FS and a representative of CRDF. Additional funding ($35,000/year for two years) starting in 2002 from the Civilian Research and Development Foundation has been used to support salaries and exchange visits for Russian collaborators. This replaced and supplemented funds formerly obtained from the Forest Service for salaries and supplements NASA support for travel and fieldwork.
- **New study sites were established (Govorkova and Khreptova) to replace the original experimental burn site in the Boguchany area.** The Govorkova site is an upland dry site, in contrast with the lowland dry forest at Yartsevo. The Khreptova site adds a particularly important dimension, as it represents the moister end of the spectrum for Scotch pine forests --where understory trees and shrubs are more abundant and different ground cover species occur compared to the drier sites at Yartsevo and Govorkova. Data from these burns will greatly broaden the applicability of our research results and enable us to begin to evaluate the effects of site variations in Scotch pine on fire behavior, intensity, emissions, and effects.
- **In 2002, two 4-ha plots were burned at Govorkova in June, and three plots were burned at Yartsevo during July. In 2003, the final two 4-ha plots were burned in July at the moist Scotch pine site near Khreptova.** Burns ranged from low to moderate-intensity surface fires (Fig. 1 and 2) to a fire at Govorkova, which burned as a crown fire through a patch of younger trees (about 10-m high) in the middle of one study plot. The latter fire enabled us to obtain excellent data on a high-intensity fire (Fig. 2). Burns of varying fire severities are illustrated in Fig. 3. Data have been analyzed and synthesized to characterize the specific burning conditions (Table 1), and fire effects and fire behavior characteristics (Table 2) for each fire conducted in 2000-2002. Sampling conducted at all plots included: fuels, vegetation, and stand structure changes (Fig. 4a, 4b), soil characteristics, small animal populations, insects, fire damage, ground sampling of fire behavior, fire and soil temperatures, remote sensing of fire spread and fire temperature, emissions (from both ground and aircraft), and fire weather. First, second, and third-year postfire sampling was carried out on all plots burned in 2000, 2001, and 2002.
- **Six additional trees were harvested and partitioned into various fuel components and size**

classes to improve biomass regressions from earlier sampling data collected in 2001. These data will be critical both for quantifying aboveground carbon stocks from data on stand diameter and height distributions, and for estimating combustion and emissions from crown fires. A biomass regression for the initial sample of 24 trees is shown in Figure 5.

- **Stephen Baker from Hao's group in Missoula designed and built a sampling system for soil respiration.** In collaboration with Russian soil scientists, in situ soil respiration was measured before and after experimental fires, and on burns of different ages, during the 2002 and 2003 field seasons. Earlier research has shown that fire-stimulated changes in soil respiration can have significant impacts on overall carbon cycle and emissions. Results have shown that on these pine sites, soil respiration was not significantly affected immediately after low-intensity surface fires, but respiration decreased with increasing surface fire intensity and severity one year following a fire. Data from two sites two years after fire, suggest that recovery to prefire levels may take several years and may be slightly more rapid on low-intensity burn sites. (Fig. 6). Rough estimates of the annual carbon emissions from respiration (Table 3), suggest that median soil respiration on one and two-year-old fires was 1/3 to 1/2 that on unburned or recently burned plots. A decrease in soil respiration of 2 tC/ha/yr over a two year period could essentially cancel out the emissions from low intensity surface fires. .But the changes in soil respiration we observed may be relatively minor compared to the direct carbon released from high intensity surface or crown fires.
- **Stephen Baker, Yuri Samsonov, and Andrey Ivanov continued to sample gaseous and aerosol emissions from the ground and aerially (Fig. 7, 8, and 9).** We are developing a substantial database of emission factors, and smoke and aerosol chemistry for a range of burning conditions and surface fuel types, including both dry and moist sites (Tables 4 and 5). This information is critical for estimating overall emissions of various types of gases and aerosols from wildfires and different types of surface vegetation.
- **The thermocouple systems first used in 2001 continued to work well.** We have obtained temperature profiles on all burns and measured temperature penetration into the bark of selected trees during fires in 2001-2003 to improve our understanding of the mortality responses of Scotch pine to fire.
- **Preliminary analyses have been completed on infrared images obtained in 2000 and 2002.** With the help of Ji-Zhong Jin we have registered fire spread and temperature data with the underlying ground data for several experimental fires, mapped fireline intensity, fire temperatures, and rates of spread, and are beginning to compare these data with surface vegetation responses and other factors (Fig. 10). Plot data and wildfire data are being analyzed and compared in terms of temperature profiles across firelines and other features that will be of use for relating to active fire images from AVHRR (Fig. 11) or MODIS. 2003 aerial data have not yet been released by Russian authorities for use by North American investigators.
- **Field teams investigated wildfire severity and vegetation characteristics on wildfires monitored from aircraft in 2002 and 2003 and on older burns identified on ETM images.** Analysis of these wildfire data is being carried out primarily by Sukhinin. He has been able to identify key spectral characteristics of different types of disturbances and use these to develop classification methods for Landsat ETM imagery. Classification can distinguish burned areas, logged areas, unburned vegetation, agricultural sites, and urban areas. This analysis provides ground-validation data on wildfires that are being used for spectral characterization of satellite images (Fig. 12, 14, and 15).
- **In 2002, we obtained detailed spectral measurements from below and above the tree canopy to characterize wavelength signatures on burned of different ages and on different types of vegetation.** Spectral data collected by Soja on different burn sites in 2002, show unique signatures for surface fire scars of different ages of surface fires (Fig. 13), as well as for pine forest and the neighboring bogs. Results show that the spectral characteristics were not masked by the “green” overstory trees. This information will be important in interpreting fire scar information from satellite images.**An extensive dataset over a wide range of weather parameters, Russian and Canadian Fire Danger Rating indices (Table 1) and fire behavior characteristics (Table 2) has been collected.** These data show clearly the impacts of weather and fuel condition on fire behavior and resultant fuel consumption and carbon emissions. Over the twelve study sites burned in 2000-2002, estimated fuel consumption ranged from 0.96 to 3.07 kg/m^2, and carbon release from 1.1 to 15.4 t/ha. Analysis indicates that certain fire danger and fire

weather indices may be good predictors of fuel consumption as well as various fire behavior parameter **Combining fire behavior and fire effects data with fire danger indices has allowed us to develop correlations and preliminary regression models (Table 6, Fig. 16)**. These models allow us to estimate effects (such as carbon consumption) from available weather data. In what we believe is a novel approach, we plan to use these relationships in combination with remote-sensing data on fire areas and severity to estimate regional fire emissions for *Pinus sylvestris* forests.

Additional Year 4 accomplishments:

- **Oksana Masjagina from SFI designed and built a sampling system for measuring bark respiration. I**n situ bark respiration was measured before and after experimental fires to observe the fire's impact on respiration and its overall impact on carbon cycling.
- **Analysis software developed for infrared images.** Software for the processing and analysis of the raw infrared images was developed that can be used for accurately estimating fire behavior at any temporal and spatial scales during the fire. This will be very useful in deciphering fire effect/fire characterization relationships with all data.
- **Fire regime data reanalyzed.** Using a filtering process to identify fire events, a longer fire interval was estimated for our study sites than has been previously reported for similar sites in Siberia. The reanalysis increased our estimate of the fire interval from 30-35 to 50 years (Fig. 17). The new value better represents landscape fire intervals and will be an important contribution to carbon cycling modeling.
- **Initial results published.** Over 30 papers on initial project results have been published or submitted for publication (see attached list) in a combination of conference proceedings and peer-reviewed journals. Publications have appeared in both Russian- and English-language outlets.

Highlights of accomplishments:

- Six experimental burns were conducted at two dry sites, and at varying intensities, in June and July 2002. Two experimental burns were conducted in 2003 at Khreptova on a wetter site. This brings the project's total to 14 experimental burns.
- Improved sampling systems for both particulates (aerosol) and gaseous emissions from helicopter and on the ground continued to deliver excellent data.
- An additional six trees across the full diameter range were harvested and partitioned into various fuel components and size classes to improve biomass data and regressions.
- All field data from the 2000-2002 field seasons have been analyzed and exchanged between North American and Russian partners. Analysis of 2003 data is ongoing.
- By combining fuels, fire weather, and fire behavior data from all twelve fires burned in 2000-2002, we have quantified Russian and Canadian Fire Danger Rating indices and calculated fuel consumption, carbon release, and fire behavior characteristics over a wide range of fire severities. These data show impacts of weather and fuel condition that lead to three-fold differences in subsequent carbon emissions.
- Carbon emissions have ranged from 1.1-15.4 t C ha^{-1} for our surface fires, dependent upon fuel moisture conditions, showing the vast range of emissions possible during a fire. This confirms the need to account for the range in possible emissions when modeling carbon cycling.
- Soil respiration on these sites appears to decrease following fires; this decrease may effectively balance out s significant part of the direct fire emissions.
- Preliminary equations relating components of the Canadian and Russian fire danger rating systems to fuel consumption and carbon release, based on our first 12 experimental fires, continue to show great promise for combining this approach with remote sensing data on fire areas to accurately estimate regional fire emissions.
- Thermal imagery was obtained from experimental fires and from wildfires in 2002 and 2003 with a digital infrared video camera. Analysis of this imagery is ongoing with improved software.
- Analysis and methods development continued for estimating burned area from active fire and fire

scar pixels on AVHRR, MODIS, and Landsat ETM for estimating fire severity.
- Field evaluation of burn severity and forest characteristics on wildfires was conducted in 2002 and 2003 to develop data for ground-truthing of active fire imagery and ETM imagery.
- Spectral data collected in 2002 shows unique signatures between burn years that will be useful in interpreting fire scar information from remote-sensing images. Results show that the spectral characteristics were not masked by the “green” overstory trees normally left alive after low- and moderate-intensity surface fires have occurred.Results from the 2000-2002 field seasons have been presented in over 30 publications in both English and Russian, many of which are in peer-reviewed journals.
- Scientists have presented initial results at several scientific meetings, including the IBFRA meeting in Krasnoyarsk in summer, 2002 (6 papers), the spring 2002 meeting of the American Geophysical Union in Washington, DC (4 papers), the 2003 annual meeting of the Ecological Society of America, and several other conferences in Madrid, Tomsk, and Krasnoyarsk**.**
- Twelve abstracts have been accepted for presentation at the upcoming May 2004 IBFRA meeting in Alaska, including a session keynote address.

CONCLUSIONS

Overall, we are pleased with the success of this extremely complex and difficult research project. During the last two years, the project has made good progress toward accomplishing all major project objectives. Although we did not burn as many experimental sites as originally anticipated, we conducted an adequate number of burns to capture a wide range of fuel and burning conditions in Scotch pine forests of central Siberia. We have also made substantial progress in relating experimental data to information on wildfires, and in developing preliminary models that should vastly improve the capability for accurately estimating carbon emissions from fires in this very important forest type. Publications and presentations output have increased for presenting FIRE BEAR results. An external reviewer of our IBFRA paper, which is in press in MITI, described it as “a truly remarkable scientific effort.” Our mutual collaboration with Russian investigators has been excellent, including continued data sharing, and collaboration on analysis and presentation of results. We have learned from our experiences on how to operate effectively for conducting this type of research in Russia, including what is required to get the needed permissions for use of the land, for burning, for aircraft remote-sensing, and for international exchange of aircraft remote-sensing data. Due to the foreigner restrictions under which we must operate regarding aircraft-based activities, we adjusted our planning and relied on trained Russian collaborators for all aspects of aerial sampling (infrared data collection, spectrometry, and emission sampling).

While we never completely surmounted the ever-changing challenges of transferring equipment, samples, and money into (and out of) Russia, we did manage to eventually resolve most problems and were successful in achieving our main research objectives. Considering the inherent difficulties of working in Russia, we believe this project was remarkably successful in accomplishing its goals. We have developed the most comprehensive data on fire emissions, behavior, and ecosystem effects ever collected in the Siberian boreal zone, and certainly one of the best anywhere in the world. This report has presented preliminary results of many aspects of the research. Because of the complexity of the project and the types of data integration needed, data analysis is ongoing and will continue over the next year, as additional peer-reviewed papers are prepared on this important research. In the future, we hope to continue building our dataset through more experimental fires, overflights of wildfires, and analysis of multi-scale remote sensing data in other areas of Russia. While we have so far concentrated on Scotch pine sites, we hope with future funding to expand our data gathering to the larch forests, which are the most extensive forest type found in Russia. By changing forest type, we will continue to increase our understanding of the landscape extent and severity of fires and of factors affecting fire behavior and intensity, effects of fire on carbon storage, air chemistry, vegetation dynamics and structure, and forest health on these new sites. The possible differences in spectral signatures of fire scars located on different forest types need to be investigated and confirmed.

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Table 1. Ambient fire weather parameters, Russian Fire Danger System, and Canadian Forest Fire Weather Index (FWI) System component values associated with each experimental fire. Fires 4a and 4b were conducted on the same experimental plot on different days. Fire 4a did not have sufficient intensity to carry, so the remainder of the plot was saved and burned 3 days later when fuels were drier (Fire 4b). Fire 10P was a small point ignition fire that was carried out to provide data for initializing fire behavior models. Fire 10 was a standard experimental burn on the entire plot where Fire 10P had been ignited earlier in the same afternoon.

			Weather parameters*				Russian Fire Danger System		Canadian Forest Fire Weather Index (FWI) System components[#]					
Fire No.	Date (dd/mm/yyyy)	Ignition time (LST)	Temperature (°C)	Humidity (%)	Wind (km/h)	Rain + (mm)	Nesterov Index	Moisture Index	FFMC	DMC	DC	BUI	ISI	FWI
1	18/07/2000	15:00	26.4	21	1.0	0.0	2093	2421	92.8	50.5	393	76.4	8.5	24.7
2	26/07/2000	16:30	24.2	50	3.6	0.0	1170	1273	87.7	34.8	399	57.1	3.2	10.0
3	19/06/2001	18:00	27.0	32	10.2	2.0	2045	1583	84.9	16.9	104	24.0	3.4	6.3
4a	24/07/2001	17:00	14.1	95	3.6	0.7	461	470	73.7	27.4	193	40.4	0.9	1.8
4b	26/07/2001	15:00	18.2	43	9.7	1.0	207	297	76.0	18.9	189	30.2	1.3	2.6
5	28/07/2001	15:00	21.2	40	0.8	0.0	1034	1124	86.9	23.4	202	36.4	2.8	6.8
6	30/07/2001	14:00	22.4	52	2.6	0.0	561	651	88.1	28.2	217	42.6	3.7	9.5
7	18/06/2002	14:29	24.3	26	9.9	0.0	1057	930	91.5	17.5	113	25.2	5.8	10.3
8	19/06/2002	17:33	24.2	24	2.0	0.0	1522	1396	92.8	22.2	121	30.4	7.0	13.1
9	25/07/2002	17:45	20.6	41	9.3	0.0	797	1576	88.7	29.2	261	45.7	5.7	13.9
10P	26/07/2002	17:29	21.3	49	0.4	0.0	1041	1820	89.5	32.0	269	49.3	4.2	11.5
10	26/07/2002	18:20	23.2	37	1.2	0.0	1041	1820	87.6	31.1	269	48.2	3.1	8.7
11	30/07/2002	16:32	27.6	50	1.8	0.0	661	1340	87.7	28.5	285	45.6	3.2	8.7

* Based on solar noon weather.
[+] Rainfall in previous 24-hr period.
[a] Based on weather at ignition (see Table 1). Abbreviations are: FFMC-Fine Fuel Moisture Code, DMC-Duff Moisture Code, DC-Drought Code, ISI-Initial Spread Index, BUI-Buildup Index, and FWI-Fire Weather Index.

Table 2. Fuel consumption values and equilibrium (steady-state) fire behavior characteristics observed during each experimental fire. Values in parenthesis are for the preburn surface fuel loads and for preburn forest floor depths (L, F, and H organic layers).

Fire No.	Fuel consumption (dry weight) by category (kg/m^2)						Total carbon release (t/ha)	Fire behavior characteristics		
	Live vegetation#	Down woody debris	Litter	Forest floor	Tree Crown	Total		Depth of burn (cm)	Rate of spread (m/min)+	Fireline intensity (kW/m)*
1	0.068	0.438	0.255	2.311	0.000	3.072	15.360	6.4	9.0	9018
2	0.065	0.400	0.294	1.341	0.000	2.100	10.500	4.7	2.0	1067
3	0.027	0.034	0.098	1.194	0.000	1.353	6.765	4.4	4.9	2140
4ax	-	-	-	-	-	-	-	-	0.6	183
4b*	0.023	0.028	0.185	0.719	0.000	0.955	4.775	3.3	2.5	1156
5	0.047	0.055	0.178	0.798	0.000	1.078	5.390	3.5	2.9	1016
6	0.040	0.062	0.181	1.009	0.000	1.292	6.460	4.0	5.9	2473
7	0.032	0.192	0.159	1.140	0.000	1.523	7.615	4.6	6.5	3195
8C*	0.055	0.221	0.109	1.826	0.000	2.691	1.346	5.6	26.7	23824
8S*	0.055	0.221	0.109	1.826	0.000	2.211	1.106	5.6	6.8	4876
9	0.021	0.170	0.111	1.054	0.000	1.356	6.780	4.1	5.0	2200
10P	0.027	0.134	0.110	2.123	0.000	2.394	1.197	6.1	5.2	3987
10	0.027	0.134	0.110	2.123	0.000	2.394	1.197	6.1	-	-
11	0.048	0.252	0.185	0.719	0.000	1.421	7.105	3.9	1.4	587

Herbaceous and shrub materials growing at ground level.
+ Rate of spread values were obtained only from the rate-of-spread timers. Values represent average equilibrium spread rates.
* All low heat of combustion values have been adjusted to account for actual fuel moisture.
x Because Fire 4a was extinguished before any fuel sampling plots were consumed, there are no quantitative measurements of actual fuel consumption for this fire.
* Fireline intensity calculation for Fire 4a was based on fuel consumption estimated from Fire 4b. Fire 8C represents the portions of the fire that burned in a crowning fire, while 8S represents the portions that burned as a surface fire.

Table 3. Estimated carbon emissions from seasonal soil respiration following experimental fires. Calculations were based on the assumption that the measured respiration rates shown in Figure 6 represent a reasonable average value over a 3-month growing season.

Year of Fire	Soil Respiration (tC/ha/yr)	Standard deviation
Unburned	4.553	0.368
2000	2.146	0.874
2001	1.496	0.184
2002	4.488	0.230

Table 4. Emission factors and estimated gaseous emissions of total carbon, CO_2, CO, and methane (CH_4) for six experimental fires where aerial smoke samples were obtained. EFCO2, EFCO, and EFCH4 represent emission factors. ECO2, ECO, and ECH4 are calculated area-based emissions. MCE is the mean combustion efficiency.

Date	Fire	Total C loss (t/ha)	MCE	Total gaseous emissions (t/ha C)	$EFCO_2$ (g/kg)	ECO_2 (t/ha)	EFCO (g/kg)	ECO (t/ha)	$EFCH_4$ (g/kg)	ECH_4 (t/ha)
7/26/2001	4	4.775	0.917	4.380	1673	7.33	96.08	0.421	3.43	0.015
7/28/2001	5	5.390	0.907	4.887	1656	8.09	108.49	0.530	2.48	0.012
7/30/2001	6	6.460	0.883	5.707	1611	9.19	135.30	0.772	3.68	0.021
7/25/2002	9	6.780	0.939	6.365	1717	10.93	71.24	0.453	1.76	0.011
7/26/2002	10	1.197	0.923	1.104	1684	1.86	89.96	0.099	3.02	0.003
7/30/2002	11	7.105	0.933	6.626	1691	11.20	77.89	0.516	7.34	0.049
Average:		5.285	0.917	4.845	1672	8.10	96.50	0.465	3.62	0.019
Standard deviation:		2.187	0.020	2.022	36	3.42	23.14	0.218	1.95	0.016

Table 5. Total mass concentration (C_0) and partial concentration ($\mu g/m^3$) of microelements in aerosol emissions sampled from the 2001 experimental fires. Reference relative concentrations (RRC) refer to the amount of the element in background soils relative to iron. Experimental relative concentrations (ERC) are the element amounts on the aerosol filters relative to iron. The experimental reference ratio (ERC/RRC) represents the relative increase of an element in the aerosol smoke sample compared to the soil reference value.

Elements:	C_0	K	Ca	Ti	Cr	Mn	Fe	Co	Zn	As	Se	Br	Rb	Sr	Zr	Mo	Pb
Filter sample Mean* ($\mu g/m^3$):	50300	268	86	4.6	2.4	5.9	18.3	0.18	3.3	0.16	0.06	2.3	1.1	0.13	0.04	0.09	1.1
Standard deviation:	42500	248	70	7.0	3.2	6.1	13.7	0.37	4.1	0.29	0.10	4.4	1.2	0.15	0.10	0.19	1.1
Standard error:	7800	45	13	1.3	0.6	1.1	2.5	0.07	0.8	0.06	0.02	0.8	0.2	0.03	0.02	0.03	0.20
Reference relative concentration (RRC):	-	0.58	0.55	0.11	0.0023	0.017	1	0.0005	0.002	0.00012	0.00002	0.0007	0.004	0.001	0.0045	0.0001	n/d
Experimental relative concentration (ERC):	-	14.6	4.6	0.25	0.13	0.32	1	0.01	0.18	0.0087	0.0033	0.13	0.06	0.007	0.0021	0.005	0.058
Experimental reference ratio (ERR):	-	25.2	8.4	2.3	56.5	18.8	1	20	90	72.5	165.0	185.7	15.0	7.0	0.5	50.0	-

* Sample size = 30.

Table 6. A modified correlation matrix showing the correlation between values obtained from the two Fire Danger Systems and various fire parameters measured during the experimental fires.

Fire parameter[#]	Russian Fire Danger System		Canadian Forest Fire Weather Index System				
	Nesterov Index	Moisture Index	DMC	DC	BUI	ISI	FWI
Fuel consumption	0.6537	0.8424*	0.9412+	0.8227*	0.9281+	0.9010+	0.9414+
Depth of burn	0.7633*	0.9007+	0.8773*	0.6806	0.8437*	0.9436+	0.9445+
Rate of spread	0.5702	0.6716	0.6385	0.2309	0.5566	0.8907+	0.8235*
Fireline intensity	0.6050	0.7819*	0.8204*	0.4997	0.7623*	0.9618+	0.9393+

Fire No. 4 was eliminated from these analyses because of incomplete data.
* Significant at the 95% confidence level.
+ Significant at the 99% confidence level.

Figure 1. Pictures showing typical Scotch pine fire behavior on a dry site in central Siberia for (top) a low-intensity surface fire (Fire 3), and (bottom) a high-intensity surface fire (Fire 1). The second fire was severe enough to cause tree mortality of all trees on the site.

Figure 2. All experimental fires were surface fires other than this example. This crowning fire occurred in a dense stand of young trees growing under the main forest canopy. The fire dropped back down to the surface when it reached the end of this patch of young subcanopy trees.

Figure 3. An aerial image showing different classes of fire severity as observed by the complete crown consumption (blacken trees) resulting from the occurrence of a crown fire (extreme left), tree mortality (brown colored trees) caused by a high-intensity surface fire (central area of image), and a low-intensity surface fire resulting in no tree mortality (extreme right).

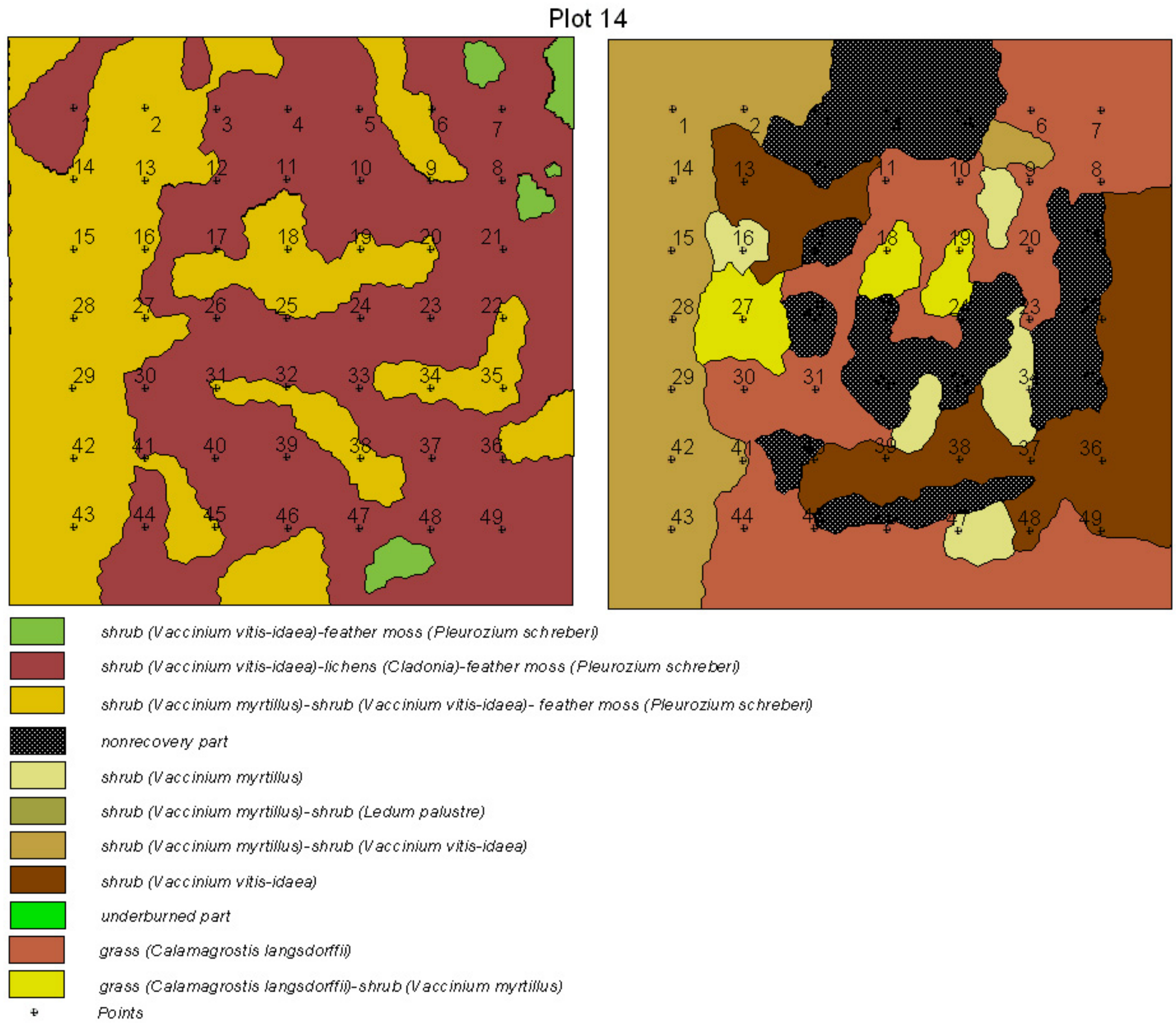


Figure 4a. Two years after a high-intensity surface fire, the ground-cover plant structure had become quite heterogeneous (right) compared to prefire structure (left). It was dominated by invader plant species, such as the grass *Calamagrostis*, or early successional species, such as *Epilobium angustifolia* (fireweed). The scale of the plot shown is 200 m/side.

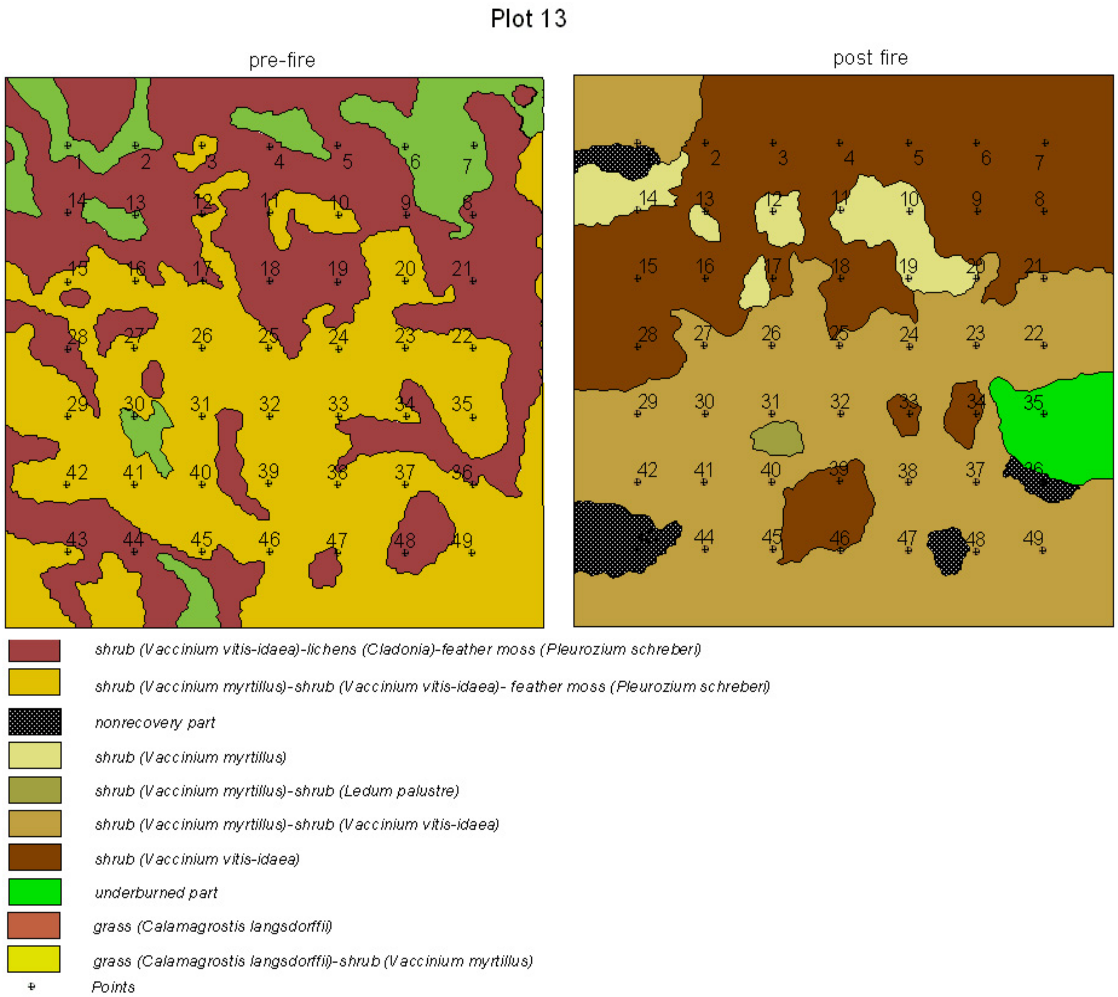


Figure 4b. Two years after a low-intensity fire, *Vaccinium vitis-idaea* and other shrub associations (right) had replaced prefire lichen/ feathermoss and small shrub/feather moss associations (left). The ground cover became much less heterogeneous compared to preburn conditions. The scale of the plot shown is 200 m/side.

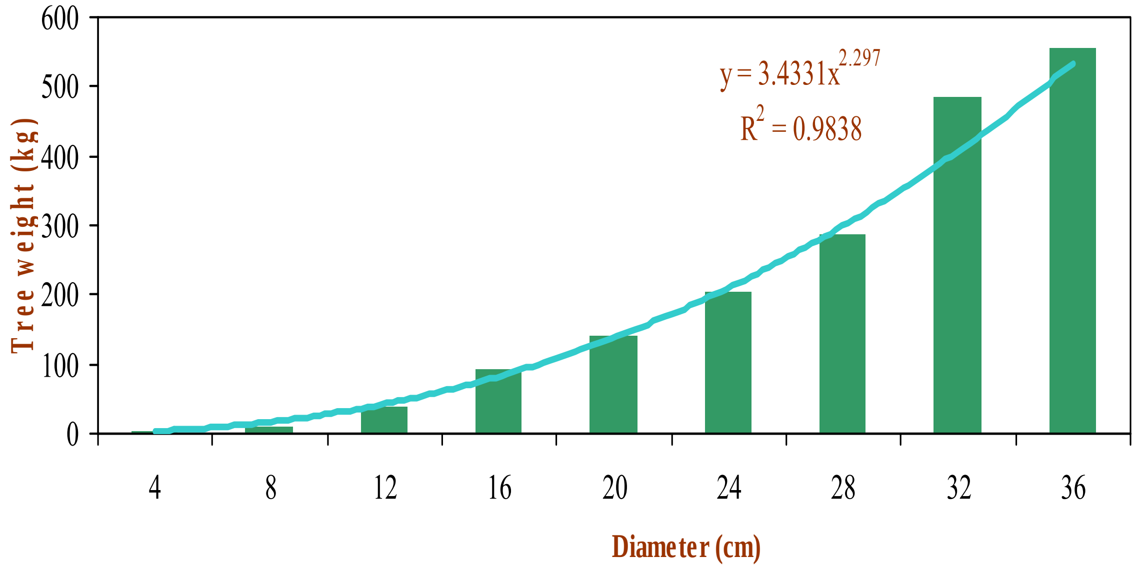


Figure 5. Relationship of tree diameter to total tree biomass. Similar regressions have been developed for relationships with foliar biomass and biomass in different fuel size classes for modeling potential effects of crown fires on emissions and carbon balance.

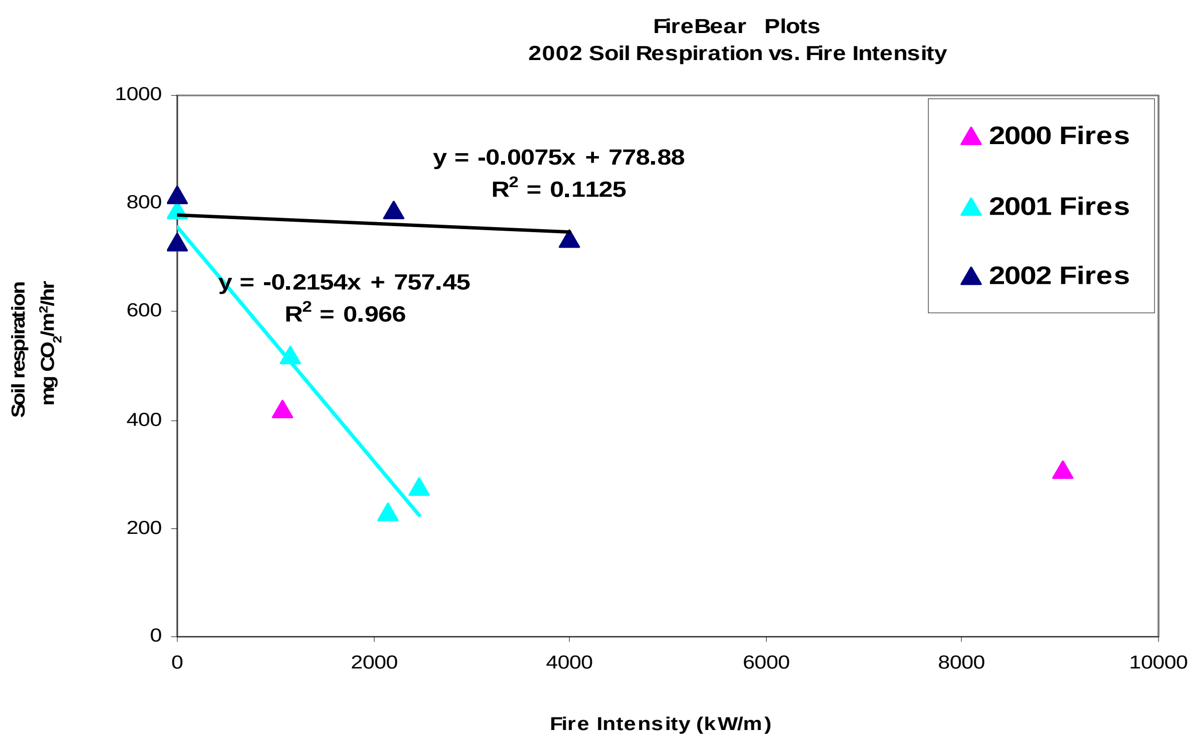


Figure 6. Soil respiration in summer 2002 on plots burned in 2000-2002. Points on Y-axis are unburned controls. Each point represents an average of 10-30 samples taken midsummer when soil moisture was high. Values range from an equivalent of about 0.5 to 2.5 t/ha of emitted carbon per year, assuming constant respiration at these levels over a 3-month period.

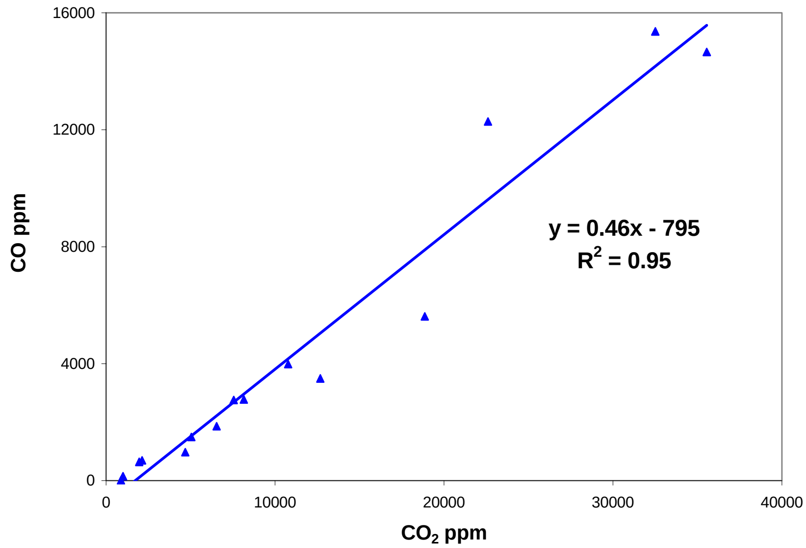


Figure 7. Carbon dioxide (CO_2) and carbon monoxide (CO) concentrations based on all 2000 ground-based samples.

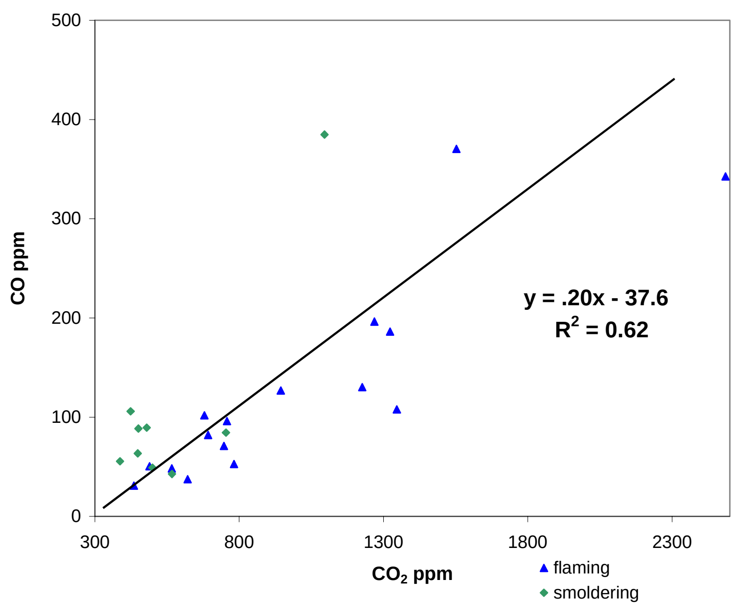


Figure 8. Carbon dioxide (CO_2) and carbon monoxide (CO) concentrations based on all 2001 ground-based samples.

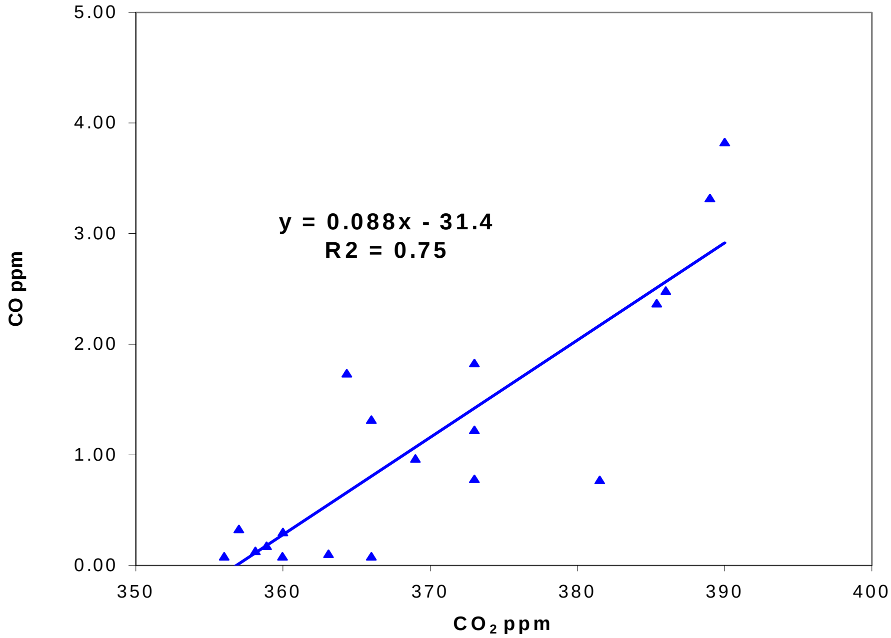


Figure 9.Carbon dioxide (CO_2) and carbon monoxide (CO) concentrations based on all 2001 aerial samples.

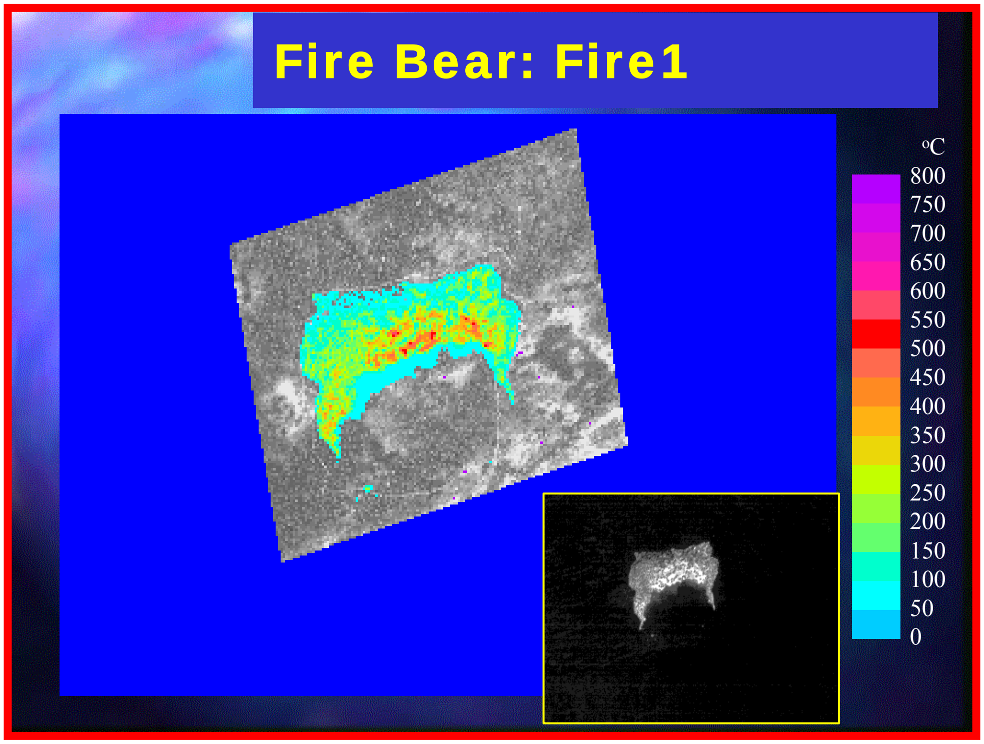


Figure 10. Aerial infrared images, taken during the experimental fires, were analyzed to quantify fire behavior parameters (e.g., rates of spread, fire temperatures, reaction intensity, etc.) that can characterize fire severity.

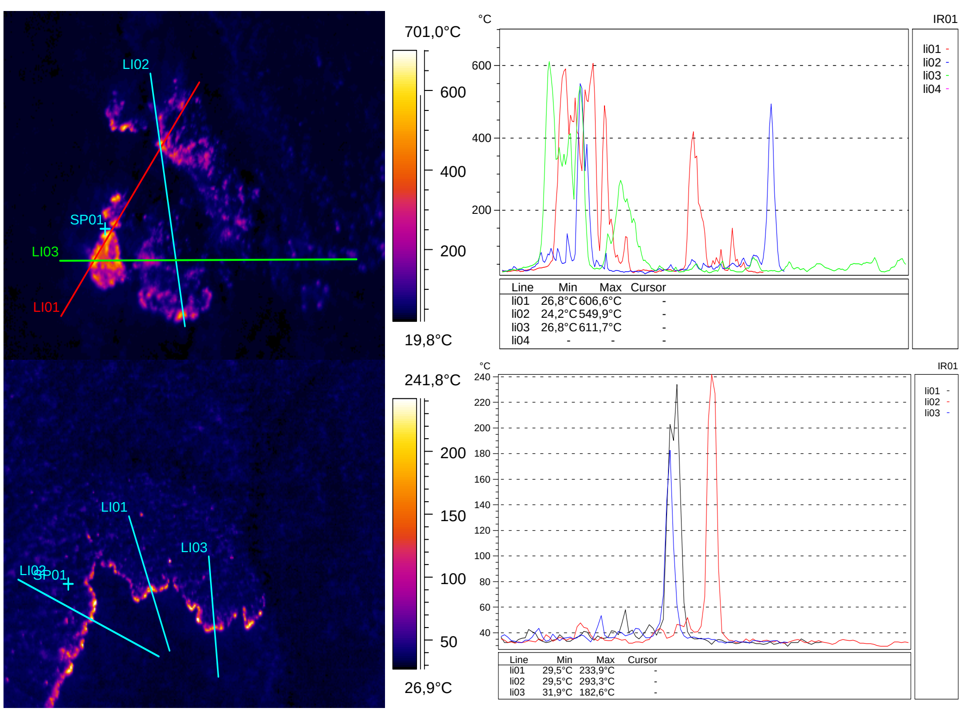
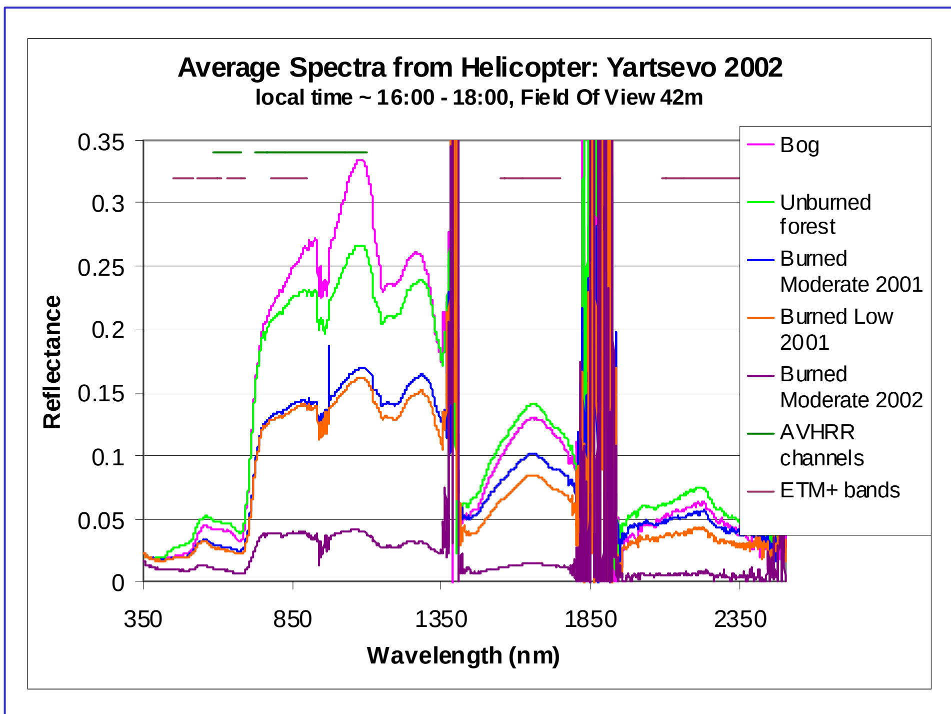


Figure 11. Aerial infrared images showing two types of wildland fire scars: 1 (top; high-intensity surface fire), and 2 (bottom; low intensity surface fire). Note the large difference in both maximum temperature and depth of the fire front between the two fires on the data analysis graph to the right of each image.

Figure 12. Estimating fire effects and emissions on a landscape scale requires detecting active fires, mapping fire scars, and developing methods to assess fire severity through a combination of ground and aerial sampling.



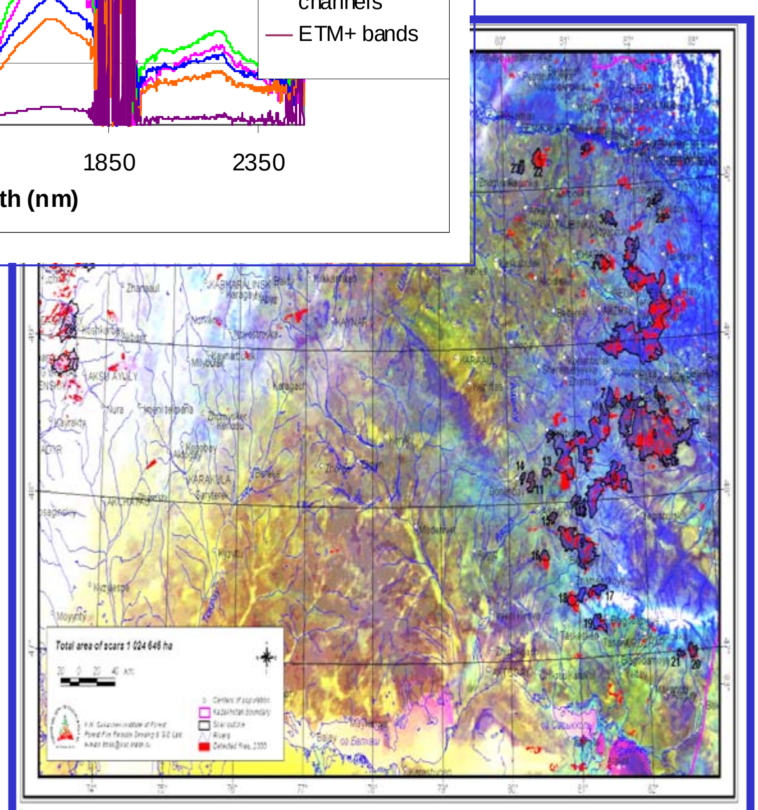


Figure 13. Spectral data were collected aerially on different burn sites in 2002. This graph shows the unique signature between burn years. This showed that the spectral signature from the burn was not entirely masked by the “green” overstory trees. This information will be important in interpreting fire scenes on remote-sensing images.

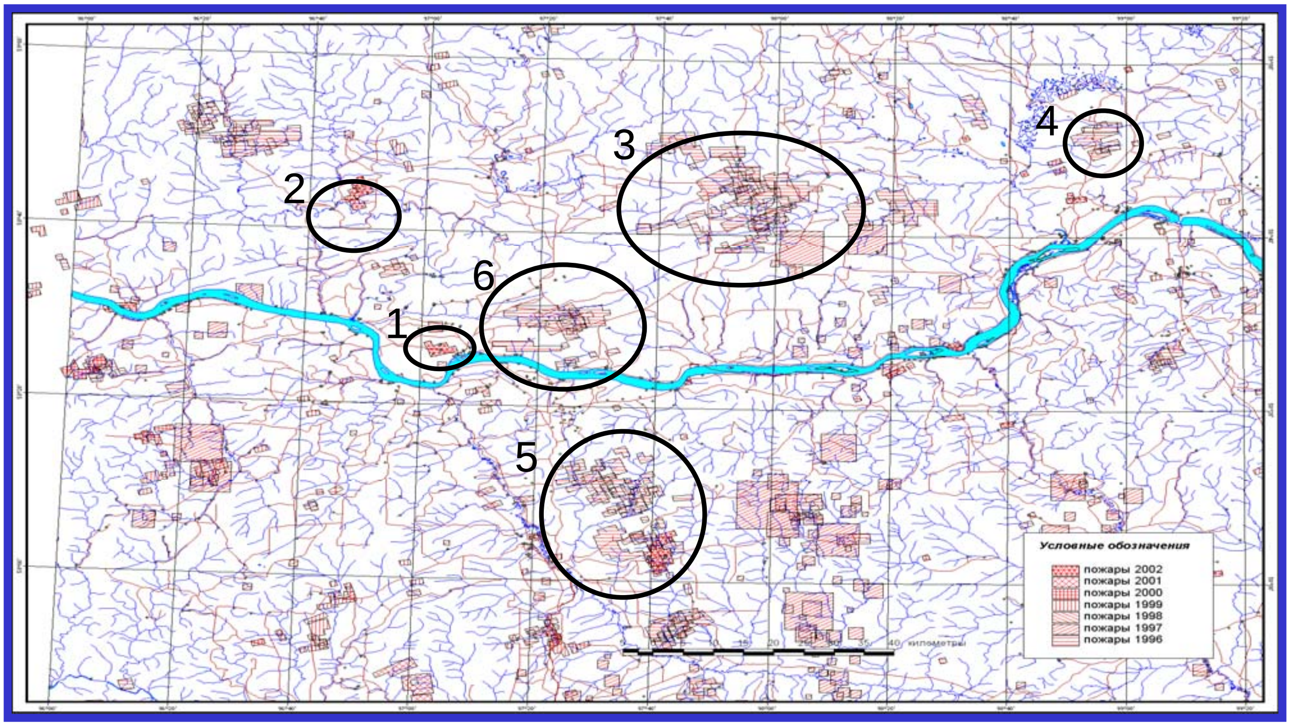


Figure 14. Location of field study areas identified from AVHRR. Scars shown are: 1- 2002 fire scar; 2- 2002 fire scar; 3- 1996 fire scar; 4- Agricultural fire 2002; 5- Scar 1996; 6- 2002 fire scar over scar of 1996 fire. Fire scars identified by AVHRR were located on Landsat ETM imagery to evaluate accuracy of burned area estimates and the ability to distinguish fire scars from other disturbances.

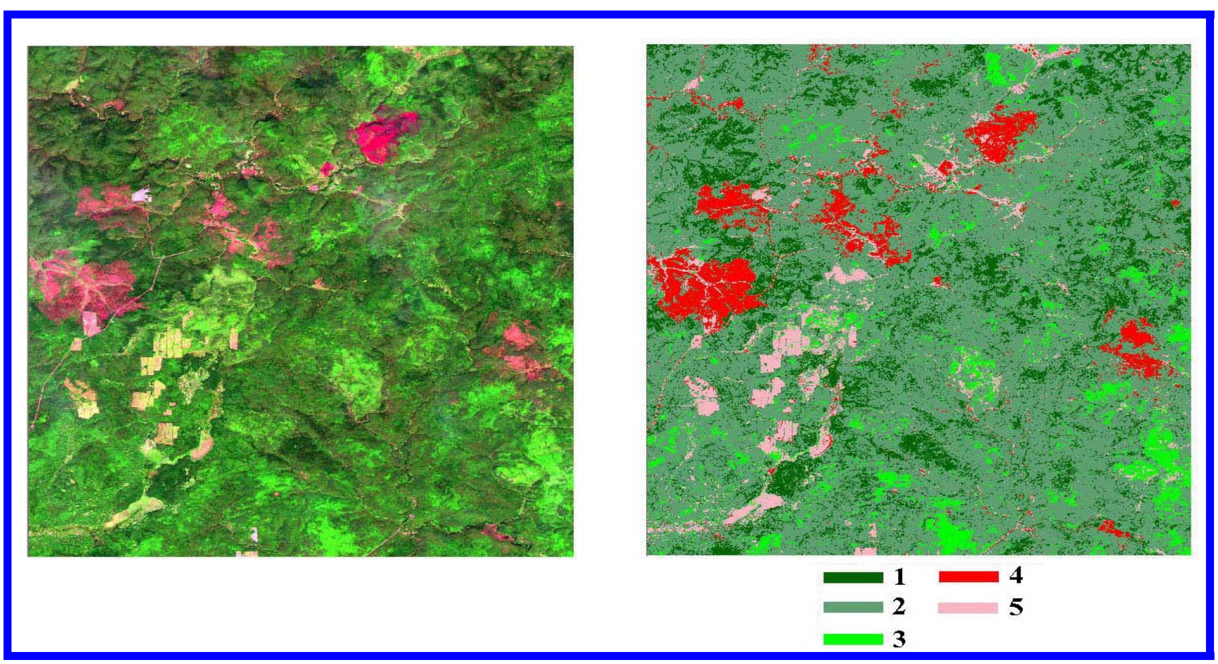


Figure 15. Fire scars identified by AVHRR were located on Landsat ETM imagery to evaluate accuracy of burned area estimates and the ability to distinguish fire scars from other disturbances. The image on the left is a portion of a Landsat image (channels 3, 4, and 7) that was classified based on training samples. The image on the right, after ground validation, shows the actual scar classification: 1 – coniferous , 2 – mixed forest, 3 – deciduous, 4 – burned areas, 5 – cuttings and other deforested areas.

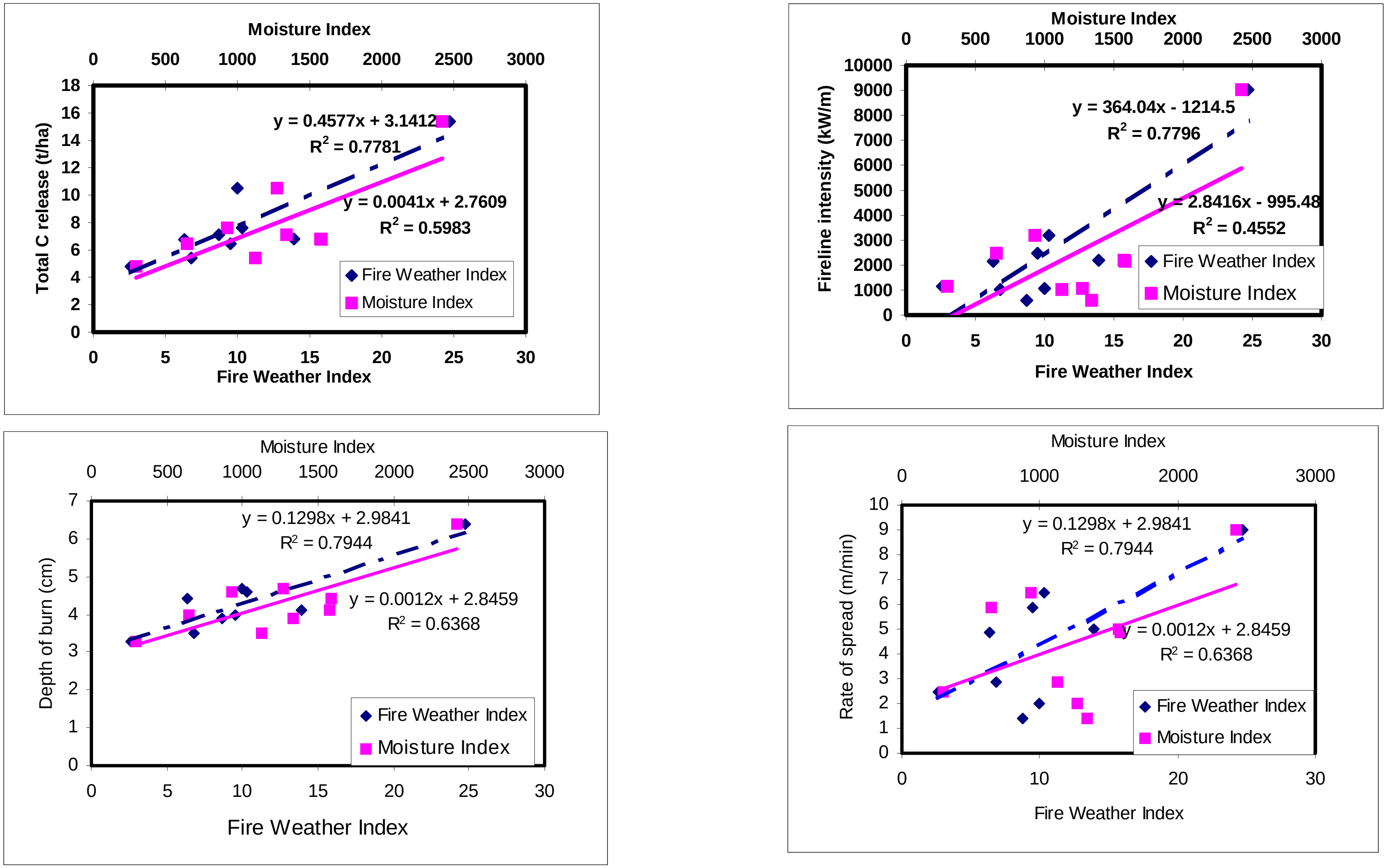


Figure 16. Relationships between carbon release, and various other parameters measured on experimental burns and the Canadian Fire Weather Index (diamonds) or the Russian Moisture Index (squares) at the time of the burns. The indices can be calculated from local weather or satellite data sources.

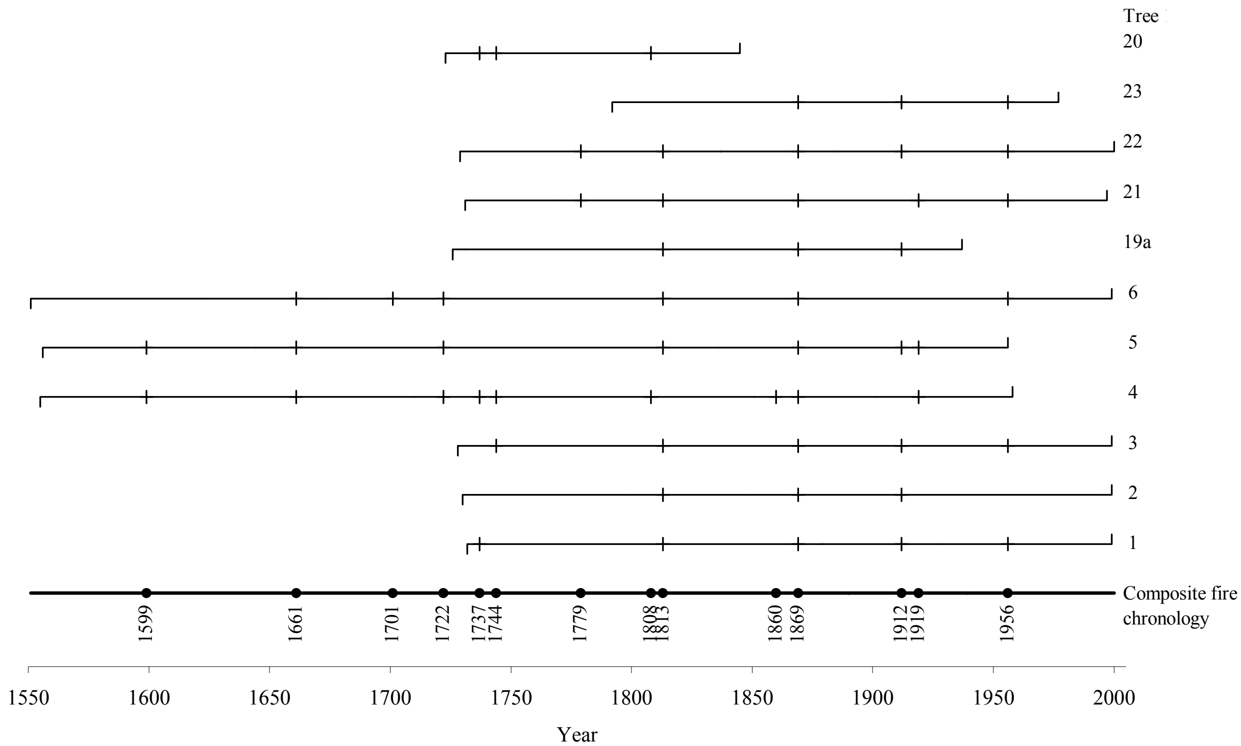


Figure 17. A fire chronology chart showing dates of fires based on fire scar and dendrochronological analysis of selected trees on and adjacent to the experimental site. These data were used to estimate a landscape-scale fire interval of 50 years for our Yartsevo study area.