Heat Transfer Into the Duff and Organic Soil

Final Project Report
FWS Agreement No. 14-48-0009-92-962

Roger D. Hungerford
William H. Frandsen
Kevin C. Ryan

USDA Forest Service
Intermountain Research Station
Intermountain Fire Sciences Lab
Missoula, Montana 59807

Performed for U.S. Fish and Wildlife Service
National Interagency Fire Center
3095 Vista Avenue, Boise, Idaho 83705

EXECUTIVE SUMMARY

On July 1, 1992 the U. S. Fish and Wildlife Service and the U. S. Forest Service, Intermountain Research Station entered into a cooperative agreement (FWS Ref. No. 14-48-0009-92-962 DCN: 98210-2-3927) to conduct a study on "Heat Transfer into the Duff and Organic Soil. The contract called for the Intermountain Research Station's Intermountain Fire Sciences Laboratory to conduct research into the ignition and consumption processes in duff and organic soils, the physical processes of heat transfer in duff and organic soils, and the abiotic and biotic effects of heat on soils. Improved models for predicting ignition and burn-out of organic soils and the penetration of heat below the combustion zone are needed.

During this project, numerous contacts were made with scientists and managers working in organic soil ecosystems. These contacts were instrumental in defining the current knowledge and the scope of research needs. Field research sites for sample collection and prescribed burning were selected in North Carolina, Alaska and the Lake States. Organic soil cores were collected from Alaska, Minnesota, Michigan, and North Carolina. Mineral soil cores with duff layers were collected from 4 sites in Idaho. Cores were used for laboratory burning experiments. Small (10 X 10 X 5 cm) samples of duff and upper organic layers for ignition testing were collected from 15 locations from Alaska to the Southeast. Samples were also used for sustained smoldering experiments, heat transfer experiments, and to study nutrient changes in response to soil heating and consumption of organics.

Forest floor materials (duff) and organic soils often ignite during fire events and produce ground fires that burn for days or even months, consume large amounts of duff or organic soil, and result in significant ecological and landscape changes. Ignition experiments conducted on organic samples from 15 locations were used to establish relationships between moisture content, inorganic content and ignition probability. Moisture and inorganic content are key factors that influence whether ignition occurs. Organic soils with organic contents above 90 percent ignite with a greater than 80 percent probability at moisture contents below 90 percent. As inorganic content increases, soils must be drier for ignition to occur. Over the range of inorganic contents we sampled, there is a 10 percent probability that ignition will occur at moisture contents from 90 to 190 percent. North Carolina pocosin soils ignite at higher moisture contents than other soils we tested.

An established ground fire advances and consumes soil at moisture contents up to 250 percent. In one pocosin prescribed burn, fire spread through surface litter (20 to 30 % moisture content), but did not ignite or consume soil under the litter with moisture contents greater than 200 %. No ground fire occurred. The uneven surface of many wetlands caused by hummocks and depressions is also important in the ignition process. Shrubs often form hummocks, which can be as much as 19 inches higher than depressions. Fuel loads are usually greater in these hummocks and conditions are more favorable for ignition.

A stirred water calorimeter heat flux sensor was developed and used to measure heat loads (heat per unit area) under burning beds of peat with different physical properties. Heat load beneath a bed increases with depth of the bed and increased bulk density. Moisture and inorganic content also influence heat load. Measurements of heat flux under smoldering fire are needed to develop and test heat flux models that are used as inputs for the soil heat transfer model.

A model to simulate heat transfer in soils and predict soil temperature profiles over time at different depths has been developed, evaluated independently, and tested in the laboratory. This

model, developed by Dr. Gaylon Campbell and others, with support from this project represents the important heat transfer processes in soil. Currently, this model is a research model requiring inputs that are not available to managers. Our goal is to "empiricize" the model to operate with input data available to managers. The "empiricized" version of the model will be included in the First Order Fire Effects Model.

Literature and personal observations indicate that large amounts of organic soil consumption can lead to significant changes in the plant community. Knowledge about specific plant species responses are somewhat limited in many wetland systems and are particularly limited with respect to fire. Observations in old burns show that dense shrub communities have been converted to open grassland types when significant amounts of soil consumption occur. The Fish Day wildfire in the Croatan NF provided an opportunity to monitor post-fire vegetation development in areas with differing amounts of soil consumption. Two post-burn measurements have been made so far and a third will be made in the fall of 1996. Preliminary data in one low pocosin shrub community show a change to a grassland community where 1.5 to 2 feet of soil was consumed.

During this project we have discussed prescribed burning with many managers and have had the opportunity to view wildfires and conduct studies on prescribed burns in Alaska and North Carolina. We found a lot of interest in the project wherever we went. Managers were particularly supportive in Alaska and the Southeast. In cooperation with the Croatan NF, The Nature Conservancy, and the State of North Carolina Division of Forestry, prescribed burning plans have been developed for experimental burns that will address some questions and concerns. One prescribed burn has been completed and the data are being analyzed. Others will be completed when the weather cooperates. Support for this project by DOI and the resulting project work has generated support for continuing research. The Missoula Fire Lab and cooperators have been funded by Seymour Johnson Air Force Base to research issues about fuel, flammability, hydrology, and soil conditions that will help them to develop a prescribed burning program at the Dare County Air Force Bomb Range. During the course of this project we hope to conduct several experimental burns to test our ideas and use as demonstrations.

Papers were presented at the 12th Conference on Fire and Forest Meteorology in 1993, the 19th Tall Timbers Fire Ecology Conference in 1993, the Southern Forested Wetlands Ecology and Management Conference in 1996, and the 20th Tall Timbers Fire Ecology Conference in 1996. Preliminary results have also been presented at fire training courses. Seven papers have been published in proceedings, peer reviewed journals, or as Forest Service publications. Several other manuscripts are in different stages of preparation for publication.

TABLE OF CONTENTS

HEAT TRANSFER INTO THE DUFF AND ORGANIC SOIL

Final Project Report

Roger D. Hungerford, William H. Frandsen
and Kevin C. Ryan

INTRODUCTION

Wildfires burn millions of acres of public land each year. Managers also apply prescribed fire to thousands of additional acres. When assessing wildfire impacts, managers need better methods for making rehabilitation decisions and for projecting long-term changes in resource outputs. They also need better methods for predicting potential impacts of prescribed fires on vegetation and site productivity. Reliable methods of evaluating many management alternatives are lacking because relationships between biological responses, preburn conditions, and fire characteristics are not available.

Consumption of organic material by fire and the resultant soil heating are significant fire effects which currently can not be accurately predicted by managers. Heat generated from a surface fire is transferred into the soil, and the amount is a function of the heat source and the soil properties. If the soil is organic it may ignite and become a source of heat. The degree of heating and effects then depend on how far the burn boundary propagates in the organic soil. If, however, the organic layers do not ignite they act as a barrier to heat penetration.

Improved models for predicting the environmental constraints on the ignition and burn-out of organic soils and the penetration of heat below the combustion zone are needed. Models that predict organic soil consumption and soil heating provide the link between fire behavior predictions and fire effects assessments. The ability to predict potential abiotic and biotic fire effects for a planned fire prescription, would enable managers to adjust prescriptions to fit the desired resource objectives.

BACKGROUND

Organic soils and mineral soils with histic epipedons are common to ecosystems from wetlands to upland forested sites. Organic layers of different thickness are formed when low temperature, high acidity, low nutrient supply, excessive water or oxygen deficiency slow the decomposition of dead plant matter. Organic soils (often generically called peat) are classified based on organic carbon content and depth (Gilliam 1991). These soils often have a root mat at the surface over horizons of highly decomposed sapric material (muck) or less decomposed fibric material (peat). An organic soil has an organic matter content greater than 20 % with a thickness greater than 16 inches (Gilliam 1991). Deep organic soils in wetlands are often greater than 5 feet thick and have soils are called histic epipedons. Many mineral soils have a surface organic horizon from 1 to 8 inches thick. This organic horizon consists of undecomposed litter over a partially decomposed fermentation layer and a mostly decomposed humus layer. Fermentation and humus layers together are called duff. Thickness depends on accumulation and decomposition rates and time since disturbance.

Fire played a significant role in the evolution and maintenance of many wetland ecosystems with organic soils. Fire is an important process affecting vegetation development, wildlife habitat, and budgets for carbon, water, and nutrients. Numerous wetland species are either adapted to survive fire or colonize during early post-fire succession. Most shrubs and many grasses and forbs readily sprout following surface fires. Other species require an ash seedbed for successful germination. Because organic detritus decomposes slowly in most wetlands, nutrients become increasingly unavailable for growth until a fire occurs. Many plant species are adapted to rapidly take up the nutrients made available by burning.

The spatial and temporal role of fire in wetlands depends on the cyclic nature of the hydroperiod, the frequency and duration of favorable fire weather, and the presence of ignition sources. How frequently a wetland burns depends on the rate of accumulation of continuous, fine, dead biomass. This varies with the site's rate of net primary production and decomposition and with the physiography of the vegetation. Many wetland areas accumulate substantial quantities of fine dead biomass. Fine dead fuels can burn intensely after only a few hours of low relative humidity, even when the underlying soil is saturated. For example, marshes and sedge meadows rapidly accumulate fine, well aerated fuels that burn readily over open water when atmospheric conditions are appropriate. Fires may spread into the adjacent wetlands from upland ecosystems that are generally drier and burn more frequently. However, ground fires are initiated only when the wetlands are drier than normal.

Wetlands characterized by annual dry periods become increasingly susceptible to burning as biomass accumulates following the last fire. In wetlands that dry annually, the mean fire free interval varies from every few years in subtropical climates where net primary productivity is high, to centuries at high latitudes and altitudes where productivity is low. Fire-return intervals in the subtropical wetlands that dry annually are in the range of five to 20 years (Wade et al 1980), except in areas of high salinity where fires are less common (Frost, 1995). Fire return intervals in wetlands of the taiga (boreal) forest zone are on the order of 50 to 120 years in continental climates and range to 500 to 1,000 years in boreal climates dominated by maritime air (Heinselman 1981; Johnson 1992). Fires that occur during nominally dry periods consume predominantly above ground biomass in surface fires and crown fires (those consuming living foliage above 2 m high). Fires that occur during extended droughts can ignite and burn deeply into organic soils (ground fires).

The occurrence of ground fire (Fig.1) in organic soils has been well documented (Cypert 1961; Ellery et al 1989; Wein 1983). If surface fires initiate ground fire in the organic soil horizons, smoldering may continue for months or even years. Extensive consumption of organic soil drastically changes vegetation (Cypert 1973; Wein 1983; Weakley and Schafale 1991). At the extreme, terrestrial habitats are converted to marshes and aquatic habitats (Cypert 1961; Otte 1981; Richardson 1991). Very little experimental work describes the processes of ground fire in enough detail that managers can predict ignition or consumption. Prescribed fire managers burn under conditions that make sustained burning of organic soil unlikely. Even so, there are numerous instances when ground fires occur unexpectedly.

Fig. 1. Ground fire in organic soils.

Numerous management problems revolve around the ignition and burnout of organic soil. Ground fires are of relatively low intensity and combustion efficiency (Ward 1990). They produce considerable smoke, which if poorly dispersed can reduce visibility, cause health problems, and violate clean air standards. Ground fires are difficult to extinguish (Artsybashev 1983). These "hold-over" fires pose considerable risk of escaping fire lines. However, sustained ground fires are naturally reoccurring ecological processes that maintain the diversity of plant and animal species and their habitats in wetland ecosystems (Christensen 1981; Christensen et al 1981). Continued suppression of ground fires may lead to undesirable ecological changes, a buildup of fuels, and to more severe wildfires. Occasional ground fires may be necessary to perpetuate prairies and open areas (Cypert 1961 and 1973; Ellery et al 1989; Hermann et al 1991). Thus, it may be both desirable and necessary to restrict the "mop-up" of smoldering organic soil in wildfires and to conduct prescribed burns designed to consume organic soil.

PROJECT HISTORY

On July 1, 1992, the U. S. Fish and Wildlife Service and the U. S. Forest Service, Intermountain Research Station entered into a cooperative agreement (FWS Ref. No. 14-48-0009-92-962 DCN: 98210-2-3927) to conduct a study on "Heat Transfer into the Duff and Organic Soil. The contract called for the Intermountain Research Station's Intermountain Fire Sciences Laboratory to conduct research into the ignition and consumption processes in duff and organic soils, the physical processes of heat transfer in duff and organic soils, and the abiotic and biotic effects of heat on soils. The specific objectives of the project were:

1. Modify and test a preliminary model to predict limits for ignition in duff and organic soil.
2. Describe the depth of organic soil consumption in terms of the physical properties of the organic soils.
3. Develop and test a model to predict heat flux into the unburned organic soil or soil at the burn boundary.

4. Complete development and testing of a preliminary physically-based soil heat and vapor transport model to predict temperature profiles in soils below the burn boundary.
5. Develop models to link post-fire visual fire severity assessments to soils heating models to predict probable fire effects on soils and biological components.
6. Determine the response of select plant response structures to heating at different phenological stages and at different soil conditions.
7. Use ignition, consumption, soil heating, and effects models developed in objectives 1 through 6 to develop a preliminary fire effects assessment system.

PROJECT ACTIVITY SUMMARY

FISCAL YEAR 1992

During the initial stages of this project, numerous contacts were made with scientists and managers working in organic soil ecosystems. These contacts were instrumental in defining the current knowledge and the scope of research needs. From these contacts, we identified two potential field research sites for conducting prescribed burns: the Alligator River/Pocosin Lakes NWRs (National Wildlife Refuge) in North Carolina and the Tetlin NWR in Alaska. Extensive sampling was conducted in Pocosin soils in North Carolina. Sampling included collecting 37 large soil cores, 5 drums of organic muck, and 48 small soil cores. They were shipped to the Fire Laboratory in Missoula, Montana. Preliminary sampling was conducted in black spruce and sedge meadow soils in Alaska. Samples were shipped to Missoula and used for ignition, combustion, heat transfer tests, and nutrient analysis.

Four sites were selected in Northern Idaho as sites representative of upland forest duff over mineral soil. We collected 58 large soil cores and returned them to the laboratory. These cores were used to study the combustion of duff and resulting heat transfer into the mineral soil, and for developing relationships between soil heating, fire severity, and fire effects. Forty samples of duff profiles from the Lolo National Forest were collected as "guinea pigs" for developing standardized laboratory heating tests using organic layers as the heat source.

Most of our laboratory equipment and parts for assembling data loggers were purchased in FY 1992. One permanent and three temporary employees were hired to provide technical support for laboratory and field experiments. Laboratory combustion experiments were initiated, and heat flux sensors were developed and tested. Cooperative studies were initiated with Dr. Gaylon Campbell, Washington State University, and Dr. Selvin Peter, University of Quebec, to develop software for modeling evolution and flux of heat during field and laboratory experiments.

FISCAL YEAR 1993

During FY 1993 work progressed well on our laboratory ignition and core burning studies with samples collected from Idaho and North Carolina. The technical help worked out well and most of the laboratory procedures were established. During the winter and spring we focused on the laboratory studies, developed study plans for field burning, tested the heat flux sensor, and assembled the data loggers for use in the field. Work progressed well on the cooperative projects with Drs. Selvin Peter and Gaylon Campbell. A new cooperative agreement with Drs. Frank Albini and Ruhul Amin at Montana State University was also developed to evaluate existing models of heat transfer and assess our understanding of the physics of the processes.

In May three of us traveled to the Lake States and selected a potential sampling and field burning site at the Seney NWR in Michigan. Mike Benscoter, from Seney NWR, served as our guide. We visited Tamarac NWR and Lake Agassiz NWR in Minnesota and made observations at a couple of peat fires (Fig. 1). In June and July we combined a sample collection trip to Alaska with a prescribed fire at the Tetlin National Wildlife Refuge. Soil cores and organic samples were collected for laboratory studies. After a few unplanned rain events Larry Vanderlinden was able to ignite the 5000 acre Chisana River prescribed fire. We cooperated with the Pacific Northwest Research Team to get pre and post-burn samples within the burn area and collect data during the fire with 21 data loggers. Peat consumption, soil temperatures, and soil nutrient data were collected.

A pocosin site for a prescribed burn study was located on the Croatan National Forest in North Carolina. A study plan for the site was developed. A cooperative agreement was initiated with Dr. Norman Christensen at Duke University to evaluate vegetation changes associated with different burning levels in pocosin wetlands at the Croatan site. New contacts were also developed with the State of North Carolina Forest Service, which have been beneficial during field burning in North Carolina. Contacts with the Nature Conservancy in North Carolina were established, since they are trying to develop a prescribed fire program in the Green Swamp.

FISCAL YEAR 1994

We began FY 1994 by giving papers at the 12th Conference on Fire and Forest Meteorology and the Fire in Wetlands: 19th Tall Timbers Fire Ecology Conference. Preliminary results of this DOI (Department of Interior) project were included in these presentations. A paper (Appendix A) on, "Duff Consumption: New insights from laboratory burning" by Hungerford, Ryan, and Reardon was published in the proceedings of the 12th Conference on Fire and Forest Meteorology in 1994. The paper (Appendix B) for the Tall Timbers Conference, "Ignition and Burning Characteristics of Organic Soils" was printed in the conference proceedings.

Between the two meetings we visited the Okefenokee NWR, Georgia. We got an aerial view of recent fires and discussed opportunities for prescribed fire experiments with Ron Phernetton, refuge FMO (Fire Management Officer). Ron subsequently sent us organic soil samples for laboratory ignition tests. While on this trip we also spent two days with John Fort touring past prescribed and wildfires on St. Marks NWR, Florida. We discussed fire research needs. John also sent us organic soil samples for ignition testing.

Most of our efforts during the year were put into our laboratory experiments on ignition, consumption, and heat transfer. Ignition tests were completed for the North Carolina and Alaska samples, and samples were collected from four sites in the Lake States, two each at Seney NWR and Agassiz NWR. Laboratory burning experiments on the large cores from Idaho were nearly completed, and some North Carolina cores were burned as pilot tests to fine tune our experiments. Development of the heat flux calorimeter was completed and has been used to measure downward heat flux from organic material of different depths, bulk densities, inorganic and moisture contents.

Considerable progress was made on heat transfer modeling. The Washington State University co-op with Dr. Campbell yielded an updated model, which includes duff burning and heat transfer through the organic material. Under the cooperative agreement with Montana State University, Albini and Amin completed the analytical evaluation of several heat transfer models. Their results include several suggestions to improve performance of soil heat transfer models (Appendix G). As a result we negotiated a new co-op with Montana State University. U.S. Forest Service funds were used to fund this related effort.

In May, Hungerford participated as an instructor in an Ecological Burning Workshop in North Carolina, hosted by The Nature Conservancy (TNC). During this trip a wildfire in a pocosin was viewed along with some Nature Conservancy and State of North Carolina fire people. Later in May Hungerford, Ryan and Reardon traveled to the Fish Day wildfire on the Croatan NF, North Carolina. For several days the fire threatened to burn our plots which were scheduled for prescribed burning. Our research plots were not burned, but we were able to take advantage of the opportunity to collect samples for moisture and nutrient measurements, measure organic soil consumption, and temperatures (a report of our activities is in Appendix H). We felt it was important to take advantage of the opportunity to evaluate postburn recovery of vegetation in relation to burn severity and amount of consumption of organic material. A cooperative agreement was initiated with Margit Bucher of the North Carolina Nature Conservancy to setup plots and monitor vegetation development for the first two years. Plots will be georeferenced to aid in longterm monitoring.

In preparation for prescribed burning experiments in the Okefenokee Swamp, a cooperative agreement was initiated with Dr. Sharon Hermann of the Tall Timbers Research Station to establish plots for measuring preburn vegetation and fuels and to monitor postburn development following the burn treatments.

In June, Ryan and Reardon returned to the Tetlin NWR, Tok, Alaska to conduct a postburn evaluation and to collect nutrient samples from last year's Chisana River burn. While there, they took advantage of the opportunity to install dataloggers on the Lick Creek wildfire and to collect soil samples for nutrient analysis. We provided Larry Vanderlinden graphs of preliminary results of soil heating and nutrient changes from the 1993 Chisana River burn. Larry used these materials in an interagency training course in Fairbanks, in October.

FISCAL YEAR 1995

In FY 1995 the major effort was spent on continuing the laboratory ignition, sustained smoldering, heat flux and heat transfer studies. Burning of the Idaho cores was completed and most of the burning of the organic cores from Alaska, North Carolina, and the Lake States was completed. Considerable work was done to verify data and summarize all aspects of the laboratory work. Simulations of soil temperature profiles using the Campbell model were run and compared to experimentally measured soil temperature profiles. The results are promising.

Our efforts continued in North Carolina toward planning operational prescribed burns to provide field testing of our ignition and sustained smoldering models, and pursue our investigations of vegetation response following burns with different amounts of organic soil consumption. A cooperative effort was initiated with The North Carolina Nature Conservancy and the State of North Carolina Division of Forest Resources to establish experimental burn plots in the Green Swamp. We met several times to select a specific site and discuss prescriptions and parameters for burning in pocosins. We helped the TNC prepare the information needed to obtain a 404 permit from the Corps of Engineers to construct ditches on the site for the purpose of managing water levels for the burning experiments. A local agency (Cape Fear Resource Conservation and Development) agreed to help with the cost of constructing the ditches and the NRCS (Natural Resource Conservation Service) participated by providing the engineering support for designing the ditch system. The North Carolina Division of Forest Resources agreed to take the lead, in cooperation with TNC, in developing the burn prescriptions and conducting the burns. Cooperation was obtained from the State of North Carolina for developing prescriptions and operational prescribed burning techniques in pocosin fuels.

Some preliminary results of this work were presented this year at an Introduction to Fire Effects (Rx-340) course in Boise, at a Fire in Ecosystem Management Training session at Marana, and at an Ecological Burning Workshop hosted by the Florida Nature Conservancy in Orlando. Hungerford consulted with TNC folks in Florida and made contacts with others at the Tampa meeting on Environmental Regulation and Prescribed Fire and also spent some time with Dale Wade in the field and at the Macon Fire Lab.

FISCAL YEAR 1996

In FY 1996 we wrapped up the ignition and heat flux testing, which resulted in a number of draft manuscripts by Frandsen (See Appendices I, J, & K). The retirement, and completion of a productive career, by Dr. Frandsen culminates this work. The results will be tested in our field burns and integrated into management models. Work on burning of the organic cores was completed and preliminary data analyses were done and are reported here. Final analyses are in progress and the results will be published.

The Campbell heat transfer model seems to work well, based on laboratory testing results. We have data from field burns that will be used to test the model in the near future. We also have plans to implement a soil heating model in FOFEM (First Order Fire Effects Model) using Campbell's model as the basis, and possibly including some aspects of Peter's model.

Two years of post-burn data from the Fish Day Fire on the Croatan National Forest summarizing the effects of different levels of peat soil consumption on vegetation response are in the process of being analyzed and prepared for publication. The third post-burn sampling (two years post-burn) will be completed in the fall of 1996. Initial results are presented in this report.

Results from this project were presented again this year at the Introduction to Fire Effects Course (Rx-340) in Boise and Missoula. Some of the results were again presented at the Fire in Ecosystem Management Training at Marana. Hungerford and Ryan also presented a paper on "Prescribed Fire Considerations in Southern Forested Wetlands" at the Southern Forested Wetlands Conference at Clemson in March (Appendix I). Knowledge gained during this project and contacts made during this work resulted in additional cooperative relationships with other researchers in the

Southeast and support from the Air Force to continue research on prescribed burning in pocosin fuels.

LABORATORY RESEARCH RESULTS

IGNITION AND BURNOUT STUDIES

Forest floor materials such as litter and duff (fermentation and humus layers) on top of mineral soil, and organic soils (> 30 cm deep, often called peat) may be ignited during fire events. These ignitions may consume large amounts of duff or organic soil, and result in significant ecological and landscape changes. Moisture is a prominent factor in limiting ignition of ground fires because of the latent heat of vaporization. Inorganic material plays a similar role by absorbing heat that would have contributed to the combustion process. Moisture-dependent ignition limits reported in the literature vary from 40 to 500 percent (Table 1). Wade et al. (1980) state that the upper organic layer will ignite at less than 65 percent MC (Moisture Content on a dry weight basis). Where an ignition occurs it will sustain itself and burn layers up to 150 percent MC. This indicates that the ignition and sustained smoldering limits are different. After ignition, a well established

Table 1. Moisture related ignition or smoldering limits reported for organic soils and duff

Material	Site	Ignition Moisture (%)	Author
Organic soil	Florida	40	Bancroft 1976
Organic soil	Canada	100	Wein 1983
Organic soil	Florida	135	McMahon etal.1980
Commercial peat moss		110	Frandsen 1987
Commercial peat moss		140-310	Hawkes 1993
Organic soil	Florida	65	Wade et al. 1980
Organic soil	Russia	500	Artsybashev 1983
Duff	Russia	70	Artsybashev 1983
Duff	Idaho	< 150	Brown et al. 1985
Organic soil	Southeast U.S.	to H_20 table	Christensen 1981

smoldering front can sustain ground fire at moisture contents greater than the ignition limit. Hawkes (1993) reports ignition limits within the range 140 to 180 percent MC for his moderate heat load/short duration heat treatment for ignition of peat moss. His limit of 310 percent MC for a high heat load/long duration treatment may be the smoldering limit. Artsybashev's (1983) 70 percent MC for duff may be the ignition limit and the 500 percent for organic soil is likely the smoldering limit. Most of the literature on duff in the Northwest U.S. suggests that the ignition limit is less than 150 percent MC (Brown et al. 1985, Norum 1977, Ottmar et al. 1985). Clearly, the MC range where smoldering can be sustained is not well known and probably varies with the type of organic matter.

Sustainability of ground fire and the resulting organic consumption depend on a number of factors. Average duff MC or MC of the lower duff is thought to be the most important predictor of duff consumption (Shearer 1975, Norum 1977, Brown et al. 1985, Harrington 1987, Reinhardt et al. 1991). Reinhardt et al. (1991) concluded from their evaluation of published duff consumption equations, that less than 15 percent of duff will be consumed at average duff MC above 175 percent, while more than half will be consumed at average duff MC below 50 percent. The influence of duff MC on duff consumption did not vary significantly between data sets. Contrary to some published information, Reinhardt et al. (1991) found proportionally less consumption in deep duff than in shallow duff. However, they also noted that sometimes shallow duff layers had less than expected consumption, possibly because of incorporated mineral matter. Although previous work (Little et al. 1986, Harrington 1987, Ottmar et al. 1985) demonstrated that burnout of large woody fuels can effect duff consumption, Reinhardt et al. (1991) found that large woody fuel loading in combination with duff MC and pre-burn duff depth was not an important predictor of duff consumption. Hawkes (1993) showed that increasing the heat load resulted in ignition at higher moisture contents and greater consumption of peat moss.

Lab Ignition Experiments

Frandsen (1987) showed that the ignition limit for organic soil (peat moss) depended on both the amount of water and inorganic content mixed with the peat moss. Smoldering ignition limits are expressed graphically within the boundaries of a triangle formed by the Y-axis (moisture content), the X-axis (inorganic content), and a line passing through 110 % on the moisture axis and 81.5 % on the inorganic axis (Fig. 2). Hartford (1989) extended these findings to include dependence on inorganic type and organic bulk density.

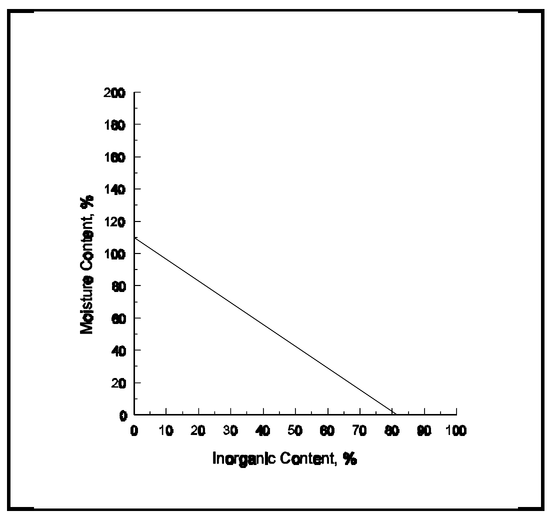

Fig. 2. Ignition limit. The line is the ignition limit for a mixture of peat moss, moisture, and inorganic material at an organic bulk density of 110 kg m^{-3}. Moisture and inorganic contents above and to the right of the ignition limit will not ignite.

Both of these studies used commercial peat moss as surrogate organic soil. It's choice rested on the fact that it is a porous fuel, propagates fire spread by smoldering combustion, and is readily available in large quantities. The goal of this experiment was to test the validity of this combustion limit on field samples. Complete results are reported in a draft manuscript (Appendix I). A brief description of the experiment and the results are discussed here.

<u>Methods</u>

Samples collected from Alaska, Montana, Minnesota, Michigan, North Carolina, Georgia, and Florida were used for ignition testing. Samples were 10 cm on a side and 5 cm deep. Samples of pocosin from one site were removed in a semiliquid form in a bucket.

Samples were tested in an insulated ignition box (Fig. 3) 10 cm X 10 cm X 5 cm. A 1 cm slice from the side was removed for moisture and inorganic determinations and then the sample was placed in the box. Dry peat moss was placed between the sample and the ignition coil located on the inside of the box midway between the top and bottom of the sample. The dry peat moss readily ignites within the three minutes of exposure to the hot coil, becoming a robust source of ignition on the side of the sample in much the same way as a lateral smoldering fire. Sample volumes were computed by measuring each dimension just prior to testing. Inorganic contents were obtained from subsamples of each individual sample being tested and measured by ashing the subsample remaining after determining moisture content. The range of inorganic contents and organic bulk densities was fixed by the location from which the samples were obtained (Table 2).

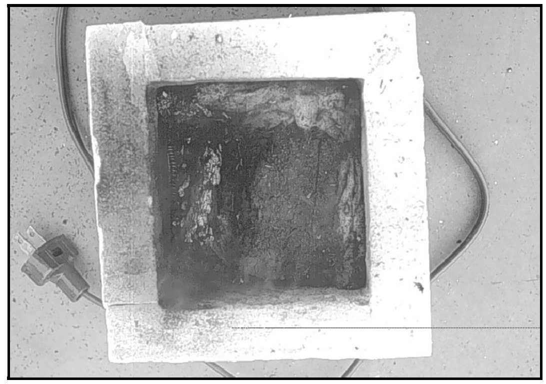

Fig. 3. An ignition box made of 2.5cm thick ceramic board holds the samples. Dry peat moss is placed between the samples and the ignition coil on the left side.

The wet pocosin samples could not be tested using the above method because the soil was fluid. These samples were freeze dried so they could be rehydrated. Samples 4cm in diameter and 2cm thick were ignited by applying a torch to ground carbon briquette material located on top of the sample. After ignition an insulating layer of ash was sprinkled over the top of the sample.

Results

A successful ignition occurred when the sample ignited, smoldering was initiated and the sample was consumed. Sustained smoldering suggests that there is sufficient heat from the smoldering process to evaporate moisture, heat inorganic material and still have enough residual heat to continue the smoldering process. Each attempted ignition was recorded as a successful ignition (1) or unsuccessful ignition (0). Thirty samples were taken from each location so that the ignition tests could span a range of moisture contents that included the ignition limit. Each sampled location yields a probability distribution of the potential for ignition. The probability distribution for the moisture and inorganic content was calculated. By arbitrarily choosing the 50 % probability level the moisture content for that probability can be derived for each location and paired with the average inorganic content for that location. These data pairs (Fig. 4) can then be compared with the ignition limit given earlier in Fig. 2.

There are 18 probability distributions, one for each sample group. Each produces a data pair as mentioned above. The general trend of the moisture content at 50 % probability versus the average inorganic content of the sample group are similar to the earlier peat moss results but shifted to higher moisture contents suggesting that these field samples will ignite at an even higher moisture content than commercial peat moss. A few sample groups are below the peat moss limit, and must be drier than commercial peat moss for ignition.

Table 2. Sampling groups described in terms of their average inorganic content, average organic bulk density, moisture content range for testing, and sampling depth for each group. Thirty samples were tested for each group.

Sample Identification	Average Inorganic Content %	Average Organic Bulk Density kg m^{-3}	Moisture Content Range %	Sample Depth cm
Sphagnum (upper)	12.4	21.8	50 - 437	0 to 5
Sphagnum (lower)	56.7	119.0	15 - 80	5 to 15
Feather Moss	18.1	42.7	0 - 191	10 to 25
Reindeer/feather moss	26.1	56.3	22 - 204	0 to 5
Sedge meadow (upper)	23.3	59.4	44 - 182	5 to 15
Sedge meadow (lower)	44.9	91.5	33 - 162	15 to 25
White spruce duff	35.9	122.0	34 - 135	0 to 5
Peat (Agassiz)	9.4	222.0	25 - 169	17 to 25
Peat muck (Agassiz)	34.9	203.0	15 - 78	12 to 20
Sedge meadow (Seney)	35.4	183.0	25 - 150	17 to 25
Pine duff (Seney)	36.5	190.0	44 - 99	0 to 5
Spruce/pine duff	30.7	116.0	54 - 134	0 to 5
Grass/sedge marsh	35.2	120.0	57 - 149	0 to 5
Southern pine duff	68.0	112.0	2 - 139	0 to 5
Hardwood swamp	18.2	138.0	5 - 139	0 to 5
Pocosin	2.5	210.0	104 - 300	10 to 30
Swamp forest	50.6	200.0	31 - 131	0 to 15
Flatwoods	80.2	120.0	0 - 54	0 to 15

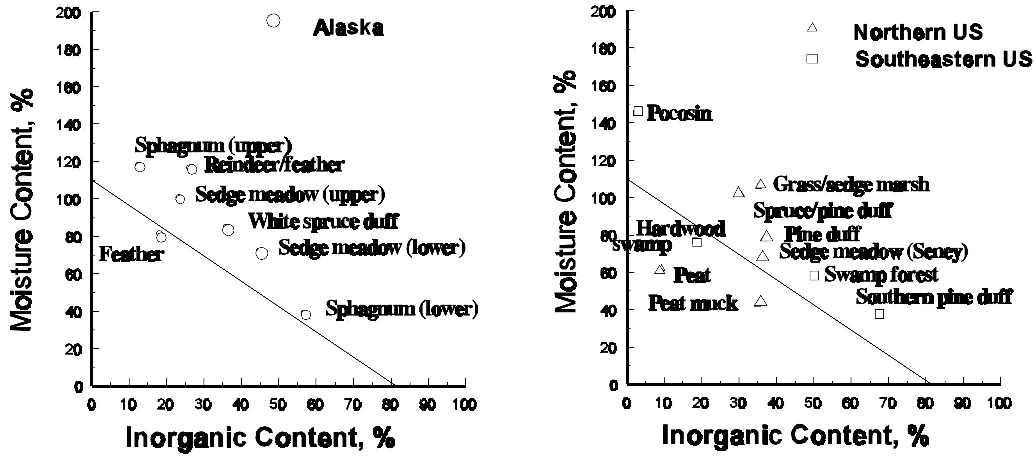

Fig. 4. The moisture content at 50% probability of ignition plotted against the average inorganic content of the sample group. The solid line represents the combustion limit for peat moss (Frandsen 1987). It is shown for comparison.

Duff Burnout Experiment

Methods

Laboratory experiments were conducted to test our ability to control duff consumption by varying duff MC and by varying moisture content of the surrounding environment. A complete description of the experiment and results were reported in a paper (Appendix A). In order to get duff samples that are as uniform as possible, twenty-three duff samples (15 cm X 15 cm 6 to 10 cm thick), were collected from a 1 m X 3 m area at a forested site near Missoula, Montana. The overstory of western larch (*Larix occidentalis*) and lodgepole pine (*Pinus contorta*) on this site was approximately 80 years old. Samples were cut from the forest floor and placed in cardboard cake boxes for transport and storage. Before burning, each sample was conditioned to the desired MC by adding water and holding them in a closed container for several days to allow for moisture equilibration. Moisture contents were targeted between 10 and 200 percent. Samples projected for a wet lower duff and a dry upper duff were conditioned in the same manner. Then a heat lamp was used to dry the upper duff. Moisture contents were calculated on a dry weight basis.

In preparation for burning, the samples were placed in an insulated container (20 cm dia.) on a dry sand bed. The space between the sides of the container and the sample was packed with vermiculite or rock wool. Moisture content of the packing material was either dry (10 percent) or wet (200 percent) and in some experiments the lower half of the packing was wet and the upper half dry. Thermocouples were placed within the duff material (at the surface, at several locations in the duff) and at the sand/duff interface. Temperature data were used to evaluate the ignition and depth of smoldering. Duff samples were ignited by placing them under a radiant heater to simulate heat from a surface fire. When ignition was assured, the heater was turned off and the sample was allowed to smolder until the duff was consumed or smoldering stopped. After burning, depth of burn and the thickness of the unburned material were measured.

Results and Discussion

Each sample was grouped by the amount of duff consumption into one of three classes: complete (100 percent), partial (25 to 75 percent), or none (0 percent). Results of 19 burns are reported. Only ash was left in the complete class.

Duff samples with MC from 10 to 100 percent packed in dry vermiculite were completely consumed and duff samples with 125 to 200 percent MC did not burn (Fig. 5). These results are in complete agreement with Frandsen (1987) for samples with low inorganic content. Further tests with duff packed in dry vermiculite included experiments where the lower duff MC was wet (> 200 %) and upper duff dry. Results showed that once smoldering was established in the upper duff complete consumption occurred.

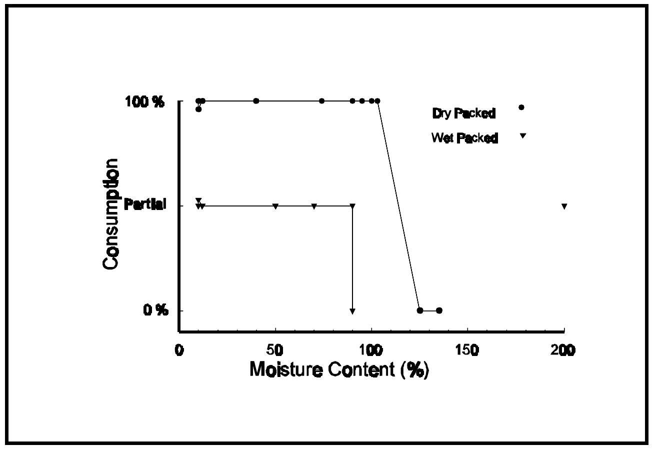

Fig. 5. Duff consumption compared to duff moisture content for samples surrounded by dry or wet vermiculite or rock wool.

Most duff samples with MC from 10 to 90 percent that were packed in wet vermiculite (200 percent) only partially burned (Fig. 5). With duff at 90 percent MC, there was no consumption when completely surrounded with wet vermiculite and only partial consumption with wet vermiculite on the lower half and dry on the upper half.

The results of these burning experiments suggest that consumption of a unit area of duff may be influenced as much by the MC of the surrounding duff as by its own MC. If the conditions of the surrounding duff affect the ignition and consumption of duff around it, our results do not indicate the dimensions of this influence zone. We hypothesize that the MC of the surrounding material influences the mass movement of moisture during the burning process, either by limiting moisture movement away from the burning zone or by replacing moisture lost during burning. It may be that unexplained variation in field observations of duff consumption could be caused by spatial variations in MC of duff bordering the points where observations were made. It is also possible that residence time of the surface fire will influence duff consumption. More rigorously designed experiments are needed to elucidate the processes and develop a complete understanding.

Sustained Smoldering Experiment

The process of smoldering and consumption of duff or peat soil is not well understood. However, our field observations and those of others (Artsybashev 1983; Wein 1983; Ellery et al 1989) provide us with a conceptual picture of the development of burn holes for field conditions (Fig. 6). A spot or a number of spots may be ignited by fire brands or by the passage of a surface or crown fire, if conditions are suitable. Smoldering may be initiated at the ground surface, in a crack or depression, or in woody material that extends into the organic soil. The location of ignition points appears chaotic, but the number of points can be expected to increase as surface dryness increases and as the duration of surface fire increases. Once ignition occurs (Fig. 6a), the smoldering front begins to burn downward and laterally, if conditions are favorable for sustained smoldering (Fig. 6b). As smoldering progresses, it creates a bowl-shaped depression (Fig. 6c). Lateral spread (most often below the surface) becomes the dominant form of spread once downward spread reaches mineral soil or MC above the smoldering combustion limits. Moisture is expected to change markedly over short lateral distances, e.g. moving from soil under the overhanging branches of a tree through the drip line to moister soil beyond. Inorganic content is not expected to change as dramatically. Consequently, lateral spread is modified by changes in moisture content. Often smoldering excavates duff below the surface leaving unburned material overhanging burned-out ash. Horizontally spreading fires may leave a thin unburned crust that will cave in under a person's weight (McMahon et al 1980). As smoldering continues, the burn hole expands laterally. Lateral spread continues until the front reaches noncombustible materials or the MC is too high. As the smoldering front moves through the organic duff material, it creates a drying zone caused by heat from the glowing zone. Pyrolysis occurs between the drying zone and the glowing zone where organics are charred and gases are released.

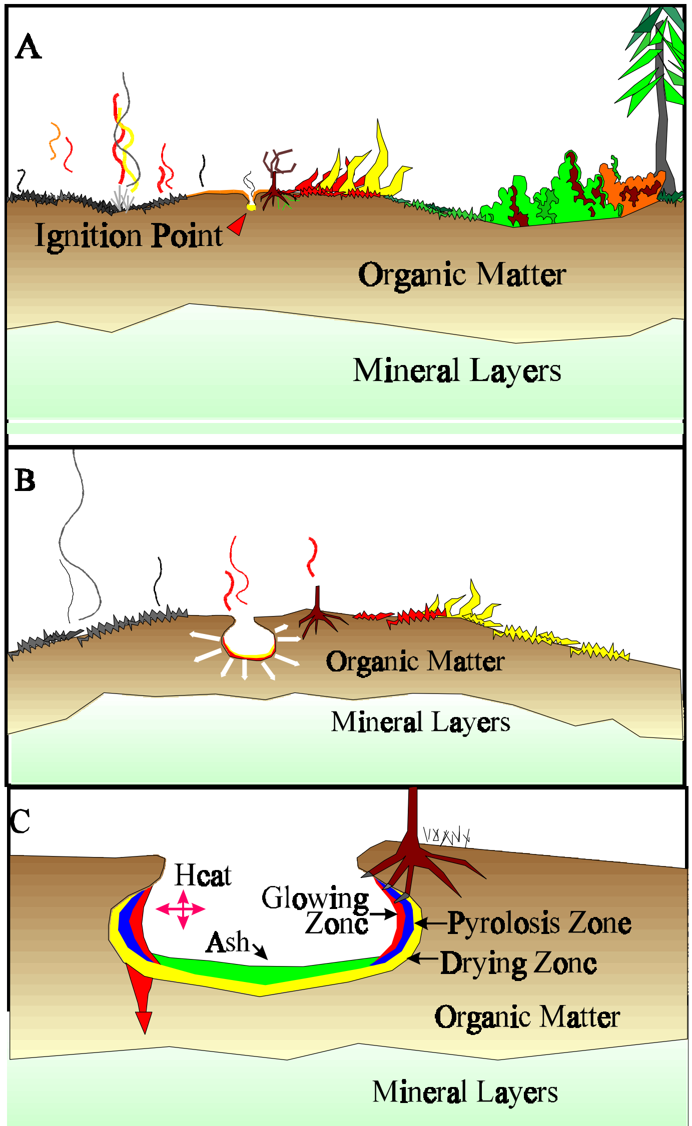

Fig 6. Schematic diagram of the smoldering process showing the typical development from an ignition point.

Methods

The objective of the sustained smoldering experiment was to identify the moisture content limit of smoldering or the moisture content of extinction. In other words, at what moisture content would an established smoldering ground fire be extinguished or not be able to continue burning? Organic cores from North Carolina (Alligator River NWR), Alaska (Tetlin NWR), Michigan (Seney NWR), and Minnesota (Lake Agassiz NWR) were burned (Fig. 7). Soil cores were obtained with a sharpened steel corer 30 cm diameter and 30 cm deep. After the sampler has been driven into the soil it was removed using a shovel. A lid and bottom plate were attached to protect the sample during transport and storage in a cooler (2-6 º C) at the Intermountain Fire Sciences Laboratory. The procedure for this experiment required us to control the depth of consumption by controlling the moisture content of the peat material. Treatments consisted of 4 different moisture regimes and an unburned control. The moisture contents selected for each treatment were based on the results of Frandsen's ignition tests reported above. The target moisture content for the first treatment was <40%MC (except < 140% MC for Alligator River). This MC was expected to result in complete consumption of the core. The moisture content for treatment two was set at a range about the 50% probability of ignition, at the inorganic content for the material. Treatment three was targeted at a moisture content level (>250%) that was higher than expected to ignite and be consumed. Moisture content values were selected from Frandsen's probability curves so the probability of ignition was 15% or less. The fourth treatment was set so the top half of the core was at a moisture content less than 40% (dry enough to sustain smoldering) and the bottom half was set at a moisture content of greater than 250%, which was expected to inhibit smoldering. In some cases (for example treatment 1 for Alligator River and treatment 3 for Seney) the actual moisture content for a core varied from the targeted MC.

Target moisture contents for each of the treatments for cores from the different locations varied based on the results of the ignition tests. Each treatment was defined by a range of moisture contents that was expected to be distinctly different from the other treatments. Moisture content of each core was measured at three depths (top, middle, and bottom) on two sides before a core was ignited. Three replications were used for each treatment and three control cores were used to obtain physical and nutrient data for comparison. Since the moisture content for some of the treatments was above the moisture content expected for ignition, we used infrared lamps to dry the upper 2 to 4 cm of the organic layer to a moisture content of 20 to 40 % so sustained smoldering could be established. Smoldering was initiated by placing a radiant propane heater above the surface for 15 to 20 minutes and igniting the litter surface with a torch during the first five minutes of heater operation. This procedure insured that smoldering was obtained on each core.

Thermocouples (16 on each side) were installed at 1- to 2- cm intervals from the surface of the core to a depth of 20 cm. Each thermocouple was inserted into the center of the core through a tube held parallel to the surface by a jig (Fig. 7). Temperatures were measured at 30-second intervals as the soil smoldered. Post-burn measurements determined ash depth, depth of burn and the actual depth of each thermocouple. Soil samples were taken for nutrient analysis at each thermocouple depth and each layer was tested for water repellency using the water drop penetration technique (De Bano 1981).

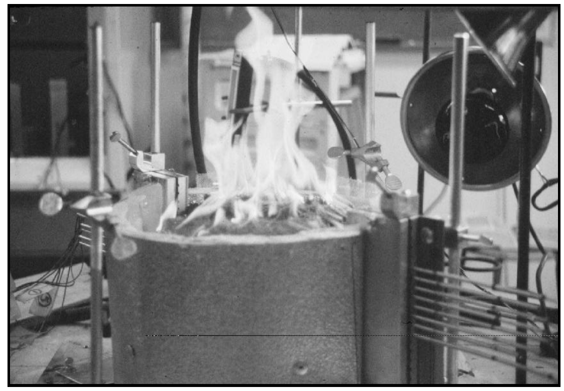

Fig. 7. Soil cores burning in the lab showing horizontal placement of the thermocouples along the side.

Results

When burning was completed, we identified the lower boundary for smoldering (interface between ash and char and unburned organic). In many cases we observed complete consumption. The depth of consumption measurements and the original core height were used to compute the percentage of the core that was consumed and the actual consumption was compared with the expected consumption (Table 3). The expected consumption amounts were based on Frandsen's ignition results. Complete consumption was expected for treatments 1 and 2. This was observed, except for the Alaska feather moss cores, where 50% consumption was observed. Cores in treatment 3 were expected to burn only the upper 2 to 4 cm and then go out, because the organic soil was too wet. With the exception of 1 of 3 cores each from Agassiz, Tetlin, and Seney, only the surface 2 to 4 cm was consumed. Consumption in these three cores was observed from 7 to 11 cm. In each of these cases it seems that the moisture content in the top layer was slightly drier (180-250% MC) than for the other two cores (250-350% MC) in the same treatment.

Table 3. Percentage of organic core consumed (ACT) by treatment for each of the four sites compared to expected (EXP) consumption. Expected consumption was based on ignition probability results for the moisture content (MC) range of the treatment. Moisture contents for treatment 4 were different in the top and bottom halves of the core.

TRT[1]	Alligator River			Tetlin NWR			Seney NWR			Lake Agassiz NWR		
	MC[2]	EXP[3]	ACT[4]	MC	EXP	ACT	MC	EXP	ACT	MC	EXP	ACT
1	16-141	100	100	10-31	100	100	1-21	100	100	4-17	100	100
2	115-180	100	100	73-130	100	50	64-85	100	90	31-106	100	100
3	241-316	10	10	223-373	10	10-30	141-276	10	1-40	204-361	10	1-10
4[5] T	80-180	50	100	4-16	50	60	3-14	50	50	6-14	50	44
4 B	180-263			200-280			137-236			160-282		

[1]TRT= Burn treatment, [2]MC= Moisture Content prior to burning, [3]EXP = Expected percent burn, [4]ACT = Actual percent consumption, [5] 4T = Top of core; 4B = Bottom of core.

Treatment 4 cores, with the upper half dry and the bottom half wet were expected to burn through the upper half then stop. Cores from Tetlin, Seney, and Agassiz followed this expected pattern. Cores from Alligator River in NC, however, burned completely. Smoldering consumed organics at moisture contents from 180 to 263 percent. This may have been expected since some of the measured moisture contents, in the bottom half, were lower than the targeted 250%. These preliminary results indicate that the upper moisture content limit for sustained smoldering is different for different organic soils. Soils from Alligator River burned at moisture contents up to 263 percent, which is higher than the ignition limit (160%) found in Frandsen's experiments. Although not conclusive, this seems to be about the limit for this soil, because nothing above 260 percent burned in treatment 3. Additional experiments are needed to repeat treatment 4 with moisture contents of the bottom half above 250 percent. Cores from the other three sites burned at moisture contents within the range predicted by Frandsen's ignition limits (70% to 110%). However, we did not have any cases between this limit and higher moisture contents (140% to 160%). These results show that soil with moisture contents above 120% from Tetlin, 140% from Marsh Cr., and 160% from Agassiz would not sustain smoldering. At this point it is not clear why cores from Alligator River will sustain smoldering at much higher moisture contents than cores from the other sites. Pocosin soils have 20% higher heat content and twice the bulk density, which may effect results.

Field observation at 15 cm ahead of a smoldering front at Seney NWR showed that it was spreading into peat with moisture contents of 89% at 5 cm below the surface and 100% at 10 cm below the surface (Fig. 8). Moisture contents at one meter ahead of the front were nearly the same. At 5 cm ahead of the front, the moisture content was 79% at 5 cm below the surface and 61% at 10 cm. These lower moistures, compared to farther distances from the front, indicate that the peat is being dried by the approaching front. Observations near a smoldering front at the Lake Agassiz NWR in Minnesota showed that the front was moving into peat with moisture contents ranging from 200 to 260%.

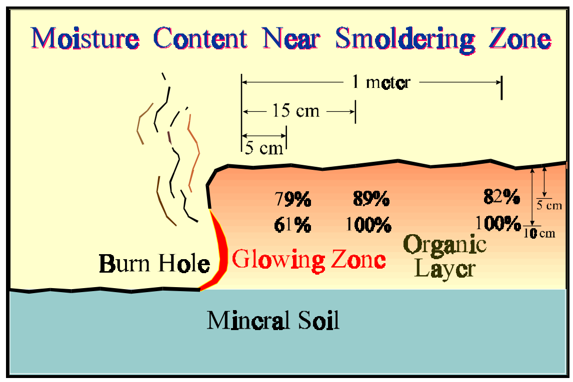

Fig. 8. Schematic diagram of soil moisture contents relative to an advancing smoldering combustion front. Moisture contents are dry weight basis.

HEAT FLUX COUPLING AND HEAT OUTPUT

Because of the dramatic presence of flaming combustion, smoldering is often overlooked as a significant source of heat. Its location adjacent to mineral soil gives it the potential to be the prime contributor of the transfer of heat into the mineral soil. It is important to consider this potential, because it has consequences that affect the biotic activity of the mineral soil, i.e, seeds and other propagules, roots, and microbes essential to nutrient cycling as well as the abiotic character of the soil such as texture.

A proper interpretation of the effect of fire at a specific location within the unburned duff and mineral soil or organic soil, should include the heat flux history at the burning boundary, thermal properties of the material and other information needed as inputs to heat transfer models.

Heat Flux Sensor

A new method for measuring heat flux was proposed that utilizes the water vapor moving downward from the combustion zone in the smoldering organic material. Downward mass transport of water vapor is collected in a stirred water filled Dewar, a vacuum insulated flask acting as a calorimeter. Water vapor condenses into the flask causing a temperature rise in the water that is sensed by thermocouples. Total transported heat energy is collected including heat energy conducted and/or convected from a porous disk covering the flask to keep the smoldering fuel from falling into the Dewar. Details are in a draft publication in Appendix J.

The stirred water calorimeter was placed below the smoldering peat sample (Fig. 9). The rate of heat energy absorbed by the stirred water calorimeter from smoldering peat moss spreading downward onto the calorimeter was determined from the product of the combined average rate of temperature rise of the two thermocouples and the combined heat capacity of the Dewar and the water in the Dewar. The rate of heat energy absorption was divided by the inner cross-sectional opening at the top of the Dewar to obtain the heat flux.

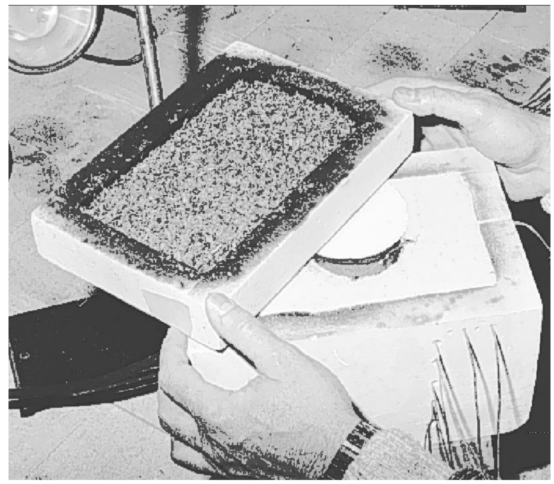

Fig. 9. Stirred water calorimeter setup showing porous disk covering the Dewar and the upper box with peat moss.

The cumulative heat load (heat per unit area, MJ m^{-2}) was obtained by integrating the heat flux over time. The instantaneous heat flux is not a smooth function of time (Fig. 10). This is due in part to the algorithm although smoothing is part of the algorithm. The flow of heat energy from the combustion process itself is also probably highly variable.

We now have a measure of instantaneous variation in heat flux for the combustion process and a smooth distribution that allows us to obtain the characteristic peak and shape of the distribution. These data can be used as boundary conditions for estimating local temperature distributions beneath smoldering porous organic fuel.

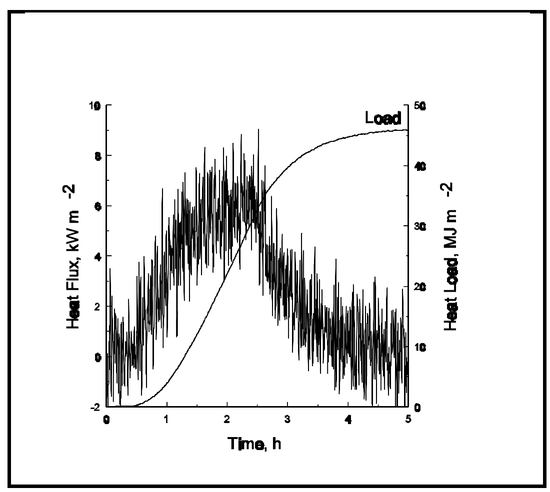

Fig. 10. Heat flux and heat load versus time.

Heat Output Testing

Methods

Organic soil in contrast to litter plays a significant role in delivering heat to the mineral soil. Flaming is commonly associated with organic bulk densities up to 50 kg m^{-3} (Rothermel 1972) and smoldering is associated with higher densities up to 200 kg m^{-3}. Natural decomposition primarily attacks the cellulosic component of these fuels leaving behind a high lignin content. Porous fuels with high lignin content have a penchant to smolder (Shafizadeh and DeGroot 1976). The goal of this experiment is to measure heat generated by smoldering porous fuel with the intent that these results can be used as a boundary condition for models that predict the flow of heat into the unburned fuel and/or the underlying mineral soil. A draft manuscript is in Appendix K.

The stirred water calorimeter was located at the center of an opened top insulated box (18 cm X 28 cm and 12.5 cm deep) constructed of ceramic board (Schneller and Frandsen 1996). The axis of the Dewar flask was vertical and normal to the box cross-section. Its outside diameter was 9 cm. The space surrounding the Dewar was filled with sand up to the lip of the Dewar - which also coincided with the top of the box. Another box open at the top and bottom was placed over the sand box whose length and width was identical to the sand box (Fig. 9). The depth of the upper box accommodates the depth of peat moss. The 18 cm X 28 cm sample surface was uniformly ignited in order to establish a flat plane of combustion as the fire moved down onto the calorimeter.

The variables examined to model the heat output of smoldering porous fuels are: organic bulk density, sample depth, moisture content, and inorganic content. Moisture content and inorganic content are important to the heat balance of smoldering combustion and are expected to play some role in the heat flowing from the smoldering combustion process. The organic bulk density dictates the amount of heat available per unit volume of the porous fuel. The product of the depth and the organic bulk density dictates the total amount of fuel available per unit planform area.

Analysis and Results

Data were collected and processed for heat load according to details in Appendix J. Numerical differentiation results in a highly variable heat flux, but retains the general shape of passing through a peak heat flux as expected (Fig. 10). This extreme variation is smoothed by integration to obtain the heat load. Heat load is the cumulative heat measured by the stirred water calorimeter normalized to the area cross sectional of the calorimeter. Data were analyzed by stepwise multiple linear regression. Measured heat loads are within the range of 50 to 100 MJ m^{-2} for depth range of 0.02 to 0.06 m and organic bulk density range of 90 to 120 kg m^{-2}. The heat load increases nonlinearly with increasing inorganic ratio and decreases linearly with increasing moisture ratio. The heat load is linear with depth and organic bulk density holding the remaining variables constant.

A 3-dimensional graph of the heat load versus moisture and inorganic ratio at a depth of 2 cm and organic bulk density of 90 kg m^{-3} shows a strong nonlinear increase in the heat load with increasing RI, inorganic ratio, and a nearly linear decrease of the heat load with increasing RM, moisture ratio, (Fig. 11). The regression fitted shape (Table Curve of SigmaPlot) is similar for all combinations of the depth and density.

The proportion of total heat generated that is measured under the fuel bed is the efficiency. The efficiency has a major dependence on the inorganic ratio (Fig. 12). It increases from 43 % to 73 % with increasing inorganic ratio at an organic bulk density of 90 kg m^{-3} and from 41 % to 63 % at a density of 120 kg m^{-3}. Frandsen (1991) also obtained an efficiency of 73 % for his measurement of the heat content of smoldering peat moss relative to the total heat content. This is surprising considering that there is a greater opportunity for heat loss in the open smoldering bed presented here. The overall relatively high fraction of heat measured by the stirred water calorimeter may be attributed to the insulating ash layer accumulating above the unburned peat moss. Added inorganic material is also likely to increase the thermal conductivity of the unburned peat moss below the combustion zone thereby increasing the amount of heat flowing downward, thus, reducing heat losses at the surface of the ash layer.

SOIL HEAT TRANSFER MODEL DEVELOPMENT

The original proposal for objective 4 stated that we would complete development of the heat transfer model that was under development in a cooperative effort between the IFSL and Washington State University, and test the model predictions of temperature profiles. The proposal stated that we would extend the research to test the model on organic soils that are of interest to the Department of Interior. The following narrative will discuss the status of this work under the following topics: 1) Soil heat transfer model development, and 2) Equipment development. Heat transfer model testing will be discussed later.

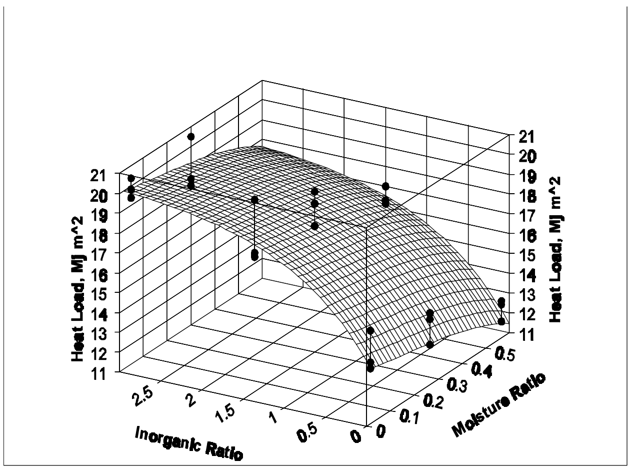

Fig. 11. Heat load versus moisture and inorganic ratios at a depth of 2 cm and organic bulk density of 90 kg m^3. Surface fit is through regression analysis of the plotted data.

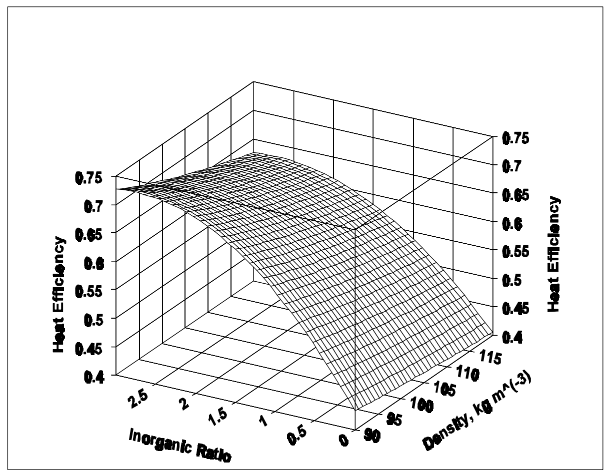

Fig. 12. Measured heat efficiency based on the intrinsic heat content of the organic mass of the peat moss samples relative to the inorganic ratio and organic bulk density.

Model Development

The model developed by Dr. Campbell from Washington State University and others provides improvements to soil science models previously presented in the literature. This model provides one of the only useful working codes available for use under the high temperature situations observed in fires. The model (Campbell and others 1995, Appendix E) includes equations for predicting apparent thermal conductivity as a function of moisture content and temperature (Campbell and others 1994, Appendix D), and a new water content-humidity relationship for soils (Campbell and others 1993, Appendix C). It incorporates the advances in theoretical and empirical modeling of transport properties over the past 20 years. These advances simplify the modeling process and reduce the number of input variables required to run the model, yet maintain the basic moisture transport phenomena that is important in the transport of heat in semi-porous media such as soils. The numerical integration scheme used is an important contribution, which is fast and numerically stable over a side range of conditions (Albini and other 1996). The latest version of the model adds realism by including a duff layer over the mineral soil and predicts the heat output from the smoldering process to provide a heat flux input for the heat transfer model in the mineral soil under the duff.

Results of initial tests, reported in Campbell and others 1995, show that the model performed well in carefully controlled laboratory tests. Soils from sand to clay, with differing mineralogies, water contents, and bulk densities were used to compare measurements and simulations. The model performed well in all cases. Since the temperature simulations are reasonable, the model appears suitable for predicting fire effects in the field. Additional testing of the model will be discussed below. Input variables for the basic model are reasonably easy to obtain. At this point the most difficult variable to obtain a reasonable value for is the heat flux at the surface. The model requires a heat flux distribution at the surface. This includes a time element, which gives the amount of heat input at each time interval, and provides the total time of heating. At the present time, in order to initialize the model we must either measure the heat flux as discussed above, or estimate the heat input based on knowledge of heat output from typical fires. Ultimately we need to do more work to model heat flux at the soil surface to use as an input to this model. Values for soil properties such as bulk density, particle density, thermal conductivity of the mineral fraction, and water content are needed. Most of these values can readily be obtained from published information about soils. Values for some other parameters used in the model can be obtained from Campbell's reports. The major input required of the user is the volumetric water content at the time of the simulation and the temperature of the soil at the start of simulation. For the variant of the model with the duff layer, some additional inputs are needed. These include, duff thickness (cm), duff density, and duff heat content. Duff density and heat content can be estimated from published information and duff thickness is the only measurement needed that is specific to the simulation.

A heat transfer model developed by Peter (1992) has been modified as a part of this project. The original model was developed by Peter on a mainframe computer system at the University of New Brunswick, which made it relatively unavailable. Peter was contracted to develop a version on a personal computer that would give the same results as the original model so we could test the model predictions as compared to laboratory experimental results. Peter's model includes components to model heat transfer in the mineral soil, similar to Campbell's model, and models heat output of burning organic material that provides the input the soil heat transfer model. We have obtained the products promised, a report (Appendix L) and the model code for the PC, but have not had an opportunity to test the predictions with our experimental data sets. This will be done in the near future and the results will be included in a subsequent manuscript.

Equipment and Technique Development

Within the course of this project we have been involved in the development and use of three pieces of equipment and the associated techniques for their use: 1) a sampler to collect undisturbed soil cores from field sites which are used in laboratory burning experiments, 2) dataloggers for measuring temperatures in prescribed fires and wildfires, and 3) a stirred water calorimeter for measuring heat flux underneath smoldering organic material. The calorimeter device and its development are described above under the section on Heat Flux Coupling and Heat

Output. We have also been involved with some cooperators (Pete Robichaud, Moscow Forestry Sciences Lab, and Dave Gasvoda, Missoula Technology and Development Center) in the development of a Duff Moisture Meter to measure moisture content of duff and organic materials. The development of this device has not been funded by this project, but we mention it here because we have spent some time on it and it relates to our need for knowledge about duff moisture contents as inputs to several of our models and since moisture content is probably the major factor determining the probability of ignition and sustained smoldering of ground fire in organic soils. This device is currently being field tested and we have applied for a patent. The following provides a brief discussion of the sampler and the datalogger.

<u>Soil Core Sampler</u>

The soil core sampler was designed to collect undisturbed soil cores (monoliths) that are 12 inches in diameter and 12 inches deep. With this sampler the natural surface material, litter, duff, etc., remains intact. The core sample can then be examined in the laboratory, to determine the characteristics of the soil, and cores can be burned using the natural organic surface materials as a source of the heat. The sampler consists of a 12 inch diameter steel pipe that is 12 inches long with a sharpened bottom edge. A slide hammer is used to drive the sampler into the soil. When the sampler is removed, the soil core remains in the sampler. When top and bottom plates are attached the sample can be transported to the lab and used as needed for experiments. Thirty seven samplers were made and used for this project. Nearly 200 cores have been collected from field sites used in this project. Seventy cores were collected from 4 sites with different soil types in N. Idaho. Organic soil cores were collected from 3 regions; 37 from pocosin in North Carolina, 40 from boreal black spruce sites in Alaska, and 47 from the Lake States in Minnesota and Michigan. About 150 of these cores have been used in laboratory experiments to date, of which 120 have been burned.

<u>Temperature Dataloggers</u>

Forty dataloggers for monitoring temperatures during burning were developed, assembled, and used during this project. This equipment was designed and built "in-house", because commercial equipment was not suitable at a reasonable price. Each datalogger has 8 chromel-alumel (Type K) thermocouple sensors to record temperatures attached to a box through a connecter. Inside the 6 X 7 X 4 inch fiberglass boxes the electronics and eight D cell batteries are located. The core of the electronics is an Onset computer chip that controls the program to collect and store the temperature data. The software program was written by IFSL personnel and modified for the desired sampling frequency. Dataloggers were buried at a depth in the soil so they won't experience any heating and the thermocouples were placed at the desired locations; in the organic layers, in the mineral soil and in some cases plant tissue. The program allows the dataloggers to be installed a few days before a planned burn. Recording does not begin until the fire reaches the top thermocouple and it reaches a temperature of 80 C, which turns on the unit and recording begins at the desired sampling rate.

Dataloggers were used in 6 prescribed fires and 3 wildfires in Alaska, the northern Rocky Mountains, and in North Carolina. Twenty-one units were used in a prescribed burn conducted by Larry Vanderlinden of the U.S. Fish and Wildlife Service in Alaska. In most cases the units have worked quite well. Our experiences were used to make improvements. Some units were loaned to hydrologists and archeologists for use in prescribed burns. The hydrologists, had better success with the units, and we learned how to make them more user friendly. A number of units have also been used by the Smoke Chemistry Project in some of their studies in Brazil and Africa. Missoula Technology and Development Center folks used 10 of the units for some studies on fire shelters and car fire experiments. The dataloggers have worked quite well and have provided useful data for this project and for cooperators. Some potential modifications have been identified that should be made to make them more useful and flexible for other projects. In cooperation with Ron Babbitt and the Smoke Chemistry Project, we may get the opportunity to modify the dataloggers. A publication that describes the dataloggers, and documents our use and testing is being prepared.

SOIL HEAT TRANSFER MODEL TESTING

Our overall strategy for testing heat transfer models includes 3 phases. Two are laboratory testing procedures and the third is field testing in operational prescribed burns. The initial laboratory phase uses sifted soil material packed in a cylinder at carefully controlled uniform moisture contents and bulk densities. Thermocouples were carefully placed at regular and known depths within the container. The soil column in the container was uniformly heated at the surface with a propane fired radiant heater.

The second procedure utilizes undisturbed soil cores sampled with the soil coring device. The heat source in these experiments is provided by burning the natural duff or organic soils and the propane fired radiant heater to simulate surface fire. Results of field testing in operational prescribed burns will be reported in subsequent manuscripts.

Fig. 13. Measured (points) and modeled (lines) soil temperatures from Campbell's lab experiments. Number near lines indicate measurement depths in mm.

Small Soil Column Experiments

The model produced by Campbell and others (1995) in cooperation with the Intermountain Fire Sciences Lab and partially supported by this project is described in the above referenced paper (Appendix E). This model is the only partially validated model readily available to investigators of wildland fire effects. The paper by Campbell and others (1995) in the Soil Science Journal describes the model and the results of model simulations compared to laboratory experimental results.

Methods

Soil was mixed to the desired moisture content, sealed in plastic, and allowed to equilibrate before being packed to a uniform bulk density in the soil columns 12 cm diameter and 15.5 cm high. Thermocouples were placed in the soil column at the desired depths below the surface to measure temperatures during the heating process. A propane fired infrared heater was used to heat the surface of the soil column to simulate heating from a surface fire. During the heating process water content changes were measured using a gamma ray attenuation technique. Experiments were run for four different soils for at least two water contents.

<u>Results</u>

The simulations were run with independently derived model parameters, so the differences between model and measured values reflect measurement uncertainty, parameter uncertainty, and model inadequacies. The main features of the heating curves (Fig. 13) and drying times are simulated by the model for the wide range of soil texture, water contents, mineral thermal conductivities, and bulk densities present in the experiments. In trials where values for the thermal properties were adjusted to see what values would be required to more closely match the data, we found that it was possible to closely match all of the measured temperature responses. The values appeared to be within the range of uncertainty in the parameters varied, so the differences were attributed to measurement or parameter uncertainty, not failure of the model.

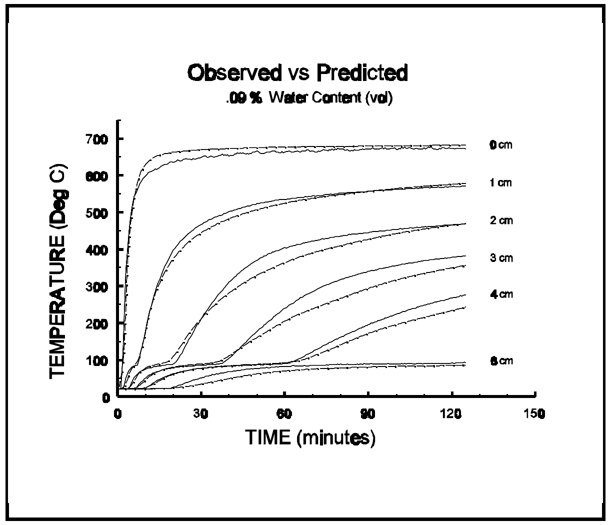

Fig. 14. Measured (solid line) and modeled (dashed line) soil temperatures for experiments at the Fire lab. Measurement depths are shown by the lines.

The water simulations show moisture content profiles that are in general agreement with measurements, but the time-course of water content changes is different for measurements and simulations. Simulations show a consistent buildup of water ahead of the drying front, while the measurements either do not show this effects or show it to be very small. We were unable to determine whether the differences were due to underestimation of water loss by the model or overestimation of the water loss by the gamma measurements. One version of the model (based on different mass flow assumptions) was able to match the drying curves more closely, but simulated temperatures were well below measured values. In other words, a drying rate consistent with the measured water contents produces a latent heat loss inconsistent with the temperature measurements. We do not know, therefore, whether the disagreement between the model and the measurements is the result of a failure in the model or the measurements. Further investigation is needed to improve our understanding of the process of moisture movement to improve the model. The present model predicts soil temperature with reasonable accuracy, and also predicts the depth of drying, so we feel it is adequate for simulating most fire effects. Similar heating experiments conducted at the Intermountain Fire Sciences Lab and simulations run with independently derived model parameters yielded a close match for temperature responses at all depths (Fig. 14).

Conceptual Model Evaluation

Through two cooperative efforts between the Intermountain Fire Science Lab and Montana State University professors Dr. Frank Albini and Dr. Ruhul Amin, we: 1) assessed differences in approach for modeling the processes of heat and mass transport in porous media across several disciplines based on a literature survey, 2) documented test exercises of Campbell's model and one other model, 3) identified opportunities for advancing the state of the art in modeling fire-driven transport of heat and moisture in soils, and 4) conducted some analytical and computational analyses to investigate the possible effects of vapor movement through buoyancy on heat transfer through moist soil in a fire-heated regime. Results for the first three items were published in a Forest Service General Technical Report (Appendix G) and are summarized below. Item four is also summarized below and the full project report is in Appendix M.

In assessing the available modeling approaches for heat and mass transport in soils exposed to heating under wildland fires it was noted that their is a distinctive difference between the mathematical models that have a soil science origin and those from the engineering and industrial process fields. These two fields of inquiry have been the major source of work on heat transfer in porous and semi-porous media. Soil science approaches ignore fluid momentum conservation. As a consequence, the body force due to buoyancy, which arises from the difference between the local static pressure gradient and the local fluid density, is not specifically included. The analysis suggested that if these processes were included in Campbell's model it might do a better job of simulating the vapor transport and thus predicting the moisture content changes that occur during heating. On the other hand, including these complicating aspects might only make a slight contribution. The engineering approach, a continuum mechanics approach, uses a more fundamental set of equations to include the momentum equations absent from the soil science models. These approaches lack representation of the diffusive mass motion of water vapor and liquid water, which should be included.

In limited testing, during this cooperative effort, we found that Campbell's model seems to perform well in predicting temperature histories at various depths, but the moisture content histories are not predicted nearly as well. The model developed by Aston and Gill (1976) was also evaluated and tested. This model does not perform well for conditions other than which it was developed, and it appears to lack generality. The working version was unstable and often gave bizarre results. Another published model (Peter 1992) was not available for testing. In the final analysis, the soil science field and specifically Campbell, have contributed the only useful models that are readily available to be used in studying wildland fire effects.

The final investigations done by Drs. Amin and Albini was a mix of analytical and computational analyses to illuminate some of the phenomenology of the effects of vapor transport through the soil in a fire-heated regime (Report by Amin and Albini is in Appendix M). These investigations were initiated by assuming the following. A uniform volume of moist soil is exposed to a constant heat source at the surface. Heating this volume causes formation of a dry zone with a distinct interface between dry and moist soil and vapor moves upward through the dry zone. A model constructed for the rate of propagation of the interface was joined with a simplified model for the rate of heat transfer through the dry zone and used to explore the effect of vapor movement through the soil. This was accomplished by doing a series of computations for rate of heat transfer through the dry zone for various dry zone layer thickness at various levels of vapor flux. The approach used allows for representation of the momentum and buoyancy phenomena that are seemingly absent from the soil science solutions.

Analyses show that the amount of heat being transmitted downward through the dry-moist interface decreases as the thickness of the dry zone increases. The heat transfer through this interface also declines with the increasing flow of vapor upward through the dry zone. On the other hand, the amount of vapor generated and the subsequent movement of the interface zone are dependent on the amount of heat transmitted from the dry zone to the moist zone. These two opposing phenomena are complicating. The net result is that if accurate predictions are to be made by a process model of heat and moisture transport in fire heated moist soils, the heat transfer through the upper, dry soil zone must be accurately modeled and the model must include an accurate representation of the response of liquid phase moisture to temperature gradients at high temperature, but below boiling. This exercise indicates that the phenomenology of buoyancy is important in the process of heat transport in semi-porous media such as soil. It was concluded, however, that including this complicating opposing phenomena in a simulation model such as Campbell's may not improve the prediction of temperature histories at different depths beneath the surface in fire heated moist soils. Therefore, we should focus on testing the Campbell model and work on adapting it for use in management applications.

Undisturbed Core Experiments

<u>Methods</u>

Undisturbed cores had the natural organic layers (litter and duff or litter and organic soil on the organic cores) at the surface. The heat source was provided by burning the natural duff and organic soils and the propane fired radiant heater. This procedure provided some element of control of the heating level, moisture content of the soil, and placement of the thermocouple temperature sensors, while including some of the natural field variations in the soil, such as roots, rocks, bulk density variations, etc. The burning experiments were conducted on 70 soil cores collected from Idaho and 16 North Carolina peat soil cores. Cores from other locations were not used for these tests. The testing procedure compares temperature observations from burning experiments with temperatures simulated using the model. Cores from Idaho were collected from four different sites and represent soil textures from a coarse granitic to fine-textured ash cap soils. Moisture contents of the soil cores were varied for the experiments. The level of soil heating was controlled by varying duff moisture content to obtain complete or partial duff consumption and adding varying amounts of heat from the radiant heater. Thermocouples were installed (16 on each side of the core) at regular depth intervals to measure temperatures during burning (Fig. 7). Temperatures were simulated by the model for the measured depths. The results for the peat cores from North Carolina reported here are from one site. Results for other sites will be reported in subsequent publications. The moisture contents of the organic soil cores used in these burning tests was greater than 250% (dry weight basis).

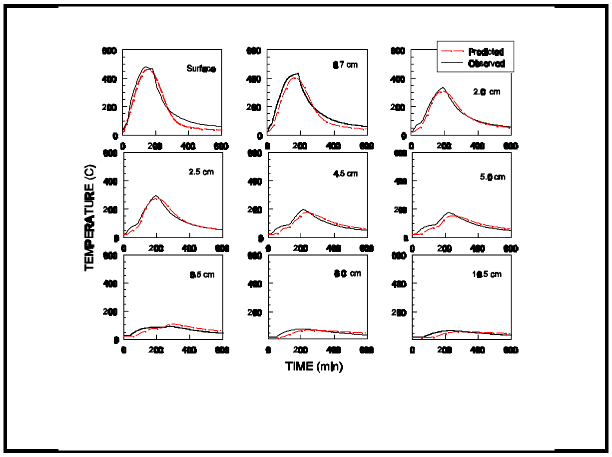

Fig. 15. Modeled temperature profiles (duff burning version) compared to measured profiles (9 depths) for an ash cap soil core from Idaho burned in the lab at 5% soil moisture.

<u>Results</u>

The original version of the Campbell model required an input of the amount of radiant heat as a boundary condition at the surface of the soil. When measurements of heat output from the burner were used as the model input, excellent agreement was obtained between modeled and measured temperature profiles in the soil. In a later version Campbell added a simulation of duff burning to compute the total amount of heat released by duff burning based on duff depth and density. A rate of heat release was then assumed to follow a Gaussian distribution, which is used to estimate the heat input at the mineral soil surface under the burning duff. This heat output provides the input for the original heat and moisture transport model.

Modeled and measured temperature profiles compared for the Idaho cores burned in the lab show excellent agreement (Fig. 15). This Idaho ash cap core was dry (5% MC) at the time of burning. Duff depth averaged 4 cm on top of mineral soil, and it was completely consumed by fire. Simulated temperature profiles were predicted using the duff simulation version. Inputs used for the model run were independently obtained from lab measurements that Campbell made for this soil type. In general, the model underpredicts slightly on the heating cycle and overpredicts on the cooling cycle. Maximum temperatures for simulations and observed are quite close for all depths. Analyses of the predicted versus the observed by regression (Fig. 16) illustrate a good fit and show the differences between the heating and cooling phases. A perfect fit would yield a line with a 0 intercept and a slope of 1. The regression line shown for each depth is fairly close to this ideal and the Coefficient of Determination (r^2) is around 0.98 for depths to 2.5 cm. At the lower depths (6.5 to 10.5 cm) the fits are not as good, but the absolute temperature discrepancy is not great.

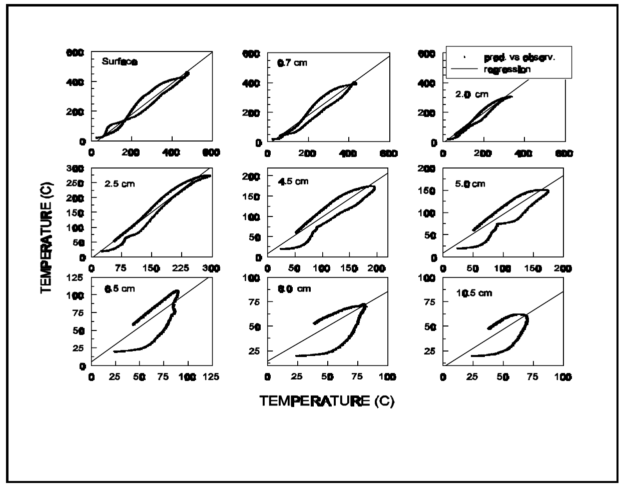

Fig. 16. Results for the predicted versus observed regression of data from figure 15.

Results of simulations using the radiant heat version for the same core, also have excellent agreement with the measured temperature profiles (Fig. 17). The curves are more closely matched for the upper 3 layers than in Fig. 15, but temperatures are overpredicted more on the cooling phase at depths from 2.5 cm to 10.5 cm. It appears that with some slight adjustment in values for parameters that influence thermal conductivity or water vapor transport, the heating and cooling phases would be more balanced. The shape of the curves and the timing of the peak temperature are matched very closely by both versions of the model.

Simulations using the duff burn version on a different soil type with wet soil also show good agreement with the measured temperature profiles (Fig. 18). Duff depth for this Idaho granitic soil core averaged 6.4 cm thick and soil moisture was 30 %. Other input values were independently obtained as described above. The simulated temperature profile at the surface of the mineral soil matched the measured profile quite well for shape and maximum temperature. With the exception of the 0.8 and 1.6 cm depths the rest of the profiles are closely matched. The differences at 0.8 and 1.6 cm appear to result from uncertainty about the depth measurements for these two thermocouples and the location of the burn boundary. The duff was not completely consumed (1-2 cm residual). Since the duff burn version of the model simulates complete duff consumption this discrepancy caused some error. Some modification of the model is needed to allow for modeling partial consumption of the organic layer.

As an initial test of the model on organic soils, simulated (radiant heat version) temperature profiles were compared with measured profiles from burning experiments of cores from Alligator River NWR in North Carolina. These organic soil cores have an organic content of 95 % or greater. The only data sets that could be used from our experiments are those where the soil was wet 0.62 (volumetric water content). Burns conducted on organic cores with lower water contents resulted in complete consumption of the organic material. Consumption of the organic material for these burning experiments ranged from 2.2 to 3.8 cm. Radiant heat input values were varied until we achieved the best match for the temperature profiles at the surface, then we compared simulated and measured temperature profiles at depths under the surface. The curve shape for temperature profiles at the surface of some of these burns show a "double hump" (Fig. 19). This is apparently a result of heat from the heater, the ignition pattern, and heat from the smoldering organic layer that was consumed. Model simulations will not reproduce this pattern, but this pattern is generally only evident at the upper layers (Fig. 19) and the profiles at deeper depths are closely matched. Figure 19 is fairly representative of most of our tests on organic soils to date. There is a tendency to give a slight overprediction (Fig. 19), but even in these cases, simulated and observed maximum temperatures are in reasonably close agreement. Comparisons for one core showed less agreement, but it may be due to discrepancies in measurement of the burn interface and location of thermocouples in relation to the interface. Based on these preliminary results the Campbell heat transfer model seems to work as well for organic soils as for mineral soils with organic layers at the surface.

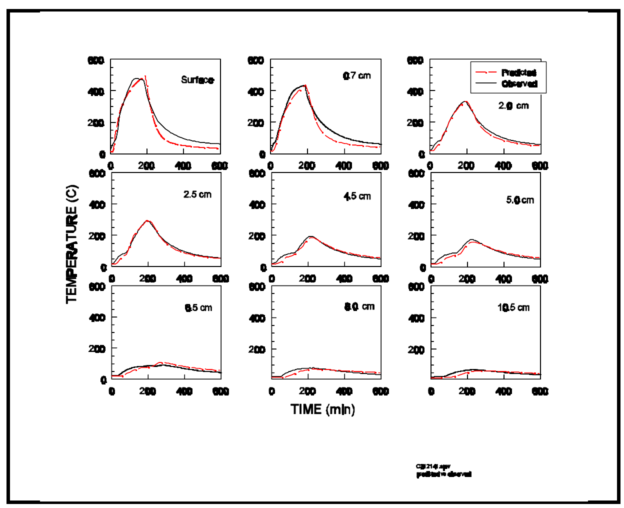

Fig. 17. Modeled temperature profiles (radiant heat version) compared to measured profiles for the same core in Fig. 15.

Plant Response to Soil Heating

The project proposal (objective 6) stated that we would do some laboratory testing of some selected plant parts from organic soils to evaluate how viability is affected by heating, moisture content, morphology, and phenological stage. We have developed lab procedures for conducting the experiments and have set up a growth chamber and an incubator for handling plant tissues, but so far we have not been able to conduct the proposed experiment. Working with cooperators, we were not able to select logical candidate species for testing that would provide useful results. After much discussion with ecologists and botanists, and a search of Fire Effects Information System (FEIS), we also concluded that we need additional information about species before we conduct these experiments. Experiments to determine relationships between soil heating and heat resistance for different morphological structures will be initiated in the future. Field observations will be discussed below in the section on Field Experiments in North Carolina.

The work we proposed with the University of Idaho was funded and resulted in a Ph.D. thesis (Balatsos, 1994; Appendix O). Two heat treatments, representing two severity levels, were

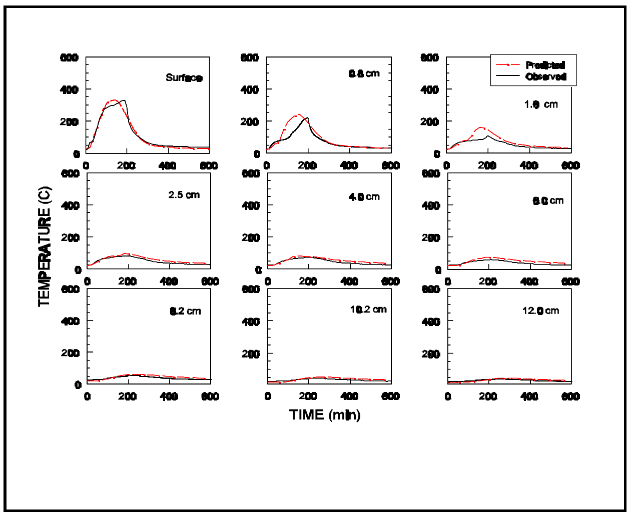

Fig. 18. Modeled temperature profiles (duff burning version) compared to measured profiles for a granitic soil core at 30% soil moisture content.

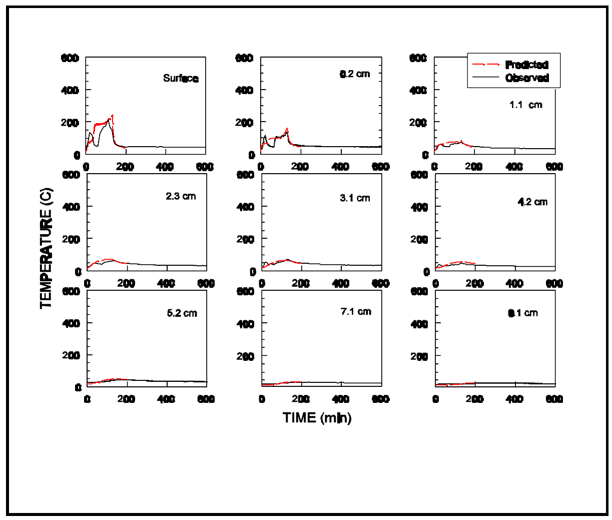

Fig. 19. Modeled temperature profiles compared to measured temperature profiles for a burned organic core from North Carolina.

applied to bunch grass plants (Agropyron spicatum) at three different phenological stages at different soil moisture contents over a two year period. Plant tissue (crown and roots) damage was evaluated by depth below the ground surface. Damage was caused by both severity treatments, but the higher severity treatment damaged root tissues at the 2 to 4 cm depth. Damage was more likely to occur in plants that were actively growing. Increased soil moisture tended to increase growth activity, thus increase the likelihood of heat damage, even though higher moisture contents resulted in reduced soil temperatures. Even though this work was done on a dry site western range bunch grass, the results indicating that actively growing tissues are more susceptible to damage probably applies to species found in wetlands also. Observations in the southeast U.S. suggest that burns during the growing season more effectively influence vegetation response. Obviously, additional work is needed to determine whether these relationships hold for plant structures with different morphologies.

Nutrient Changes in Burned Organic Cores

It was stated in the proposal (objective 6) for the project that we would do nutrient analysis on soil samples from prescribed burns to evaluate nutrient losses from soil heating. Considerable nutrient analysis has been done and is planned for prescribed burns. This work will be discussed in the section on field experiments. Our original plans did not call for soil sampling and nutrient analysis on the cores used in the core burning experiments, but we included it because we were geared up to do it. Nutrient analysis was done on samples from the control cores and the treatment cores from each 2 cm layer. The study plan (Appendix P) gives a brief description of the experiments and observations. Burning and nutrient analysis for pH, Total Nitrogen, Ammonia (NH_3), Nitrate (NO_3), and Carbon have been completed for organic cores from North Carolina, Michigan, Minnesota, and Alaska, and for mineral soil cores from 4 locations in Idaho. Analysis comparing treatment results within a location and between locations have not been completed and interpreted. Once statistical analysis have been completed and interpreted the results will be published in journal articles or Forest Service publications.

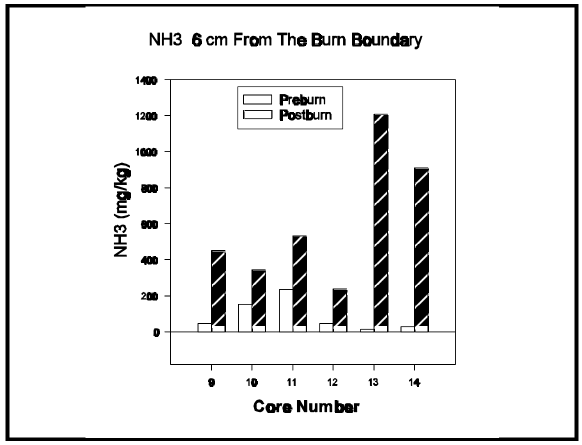

Fig. 21. Ammonia concentrations averaged for the 0 to 6 cm layer below the burn boundary from Lake Agassiz.

Preliminary results indicate that pre-burn NH_3 levels are higher in the surface 5 to 7 cm layer than in deeper layers, and levels are higher in the surface layers from Lake Agassiz and Tetlin than from Alligator River or Seney (Fig. 20). Comparison of post-burn NH_3 concentrations in the 6 cm thick layer below the burn boundary with the pre-burn concentrations from the same layer, show large increases in NH_3 (Fig. 21). The general pattern is the same for all four locations as shown for Lake Agassiz in Fig. 21. Increases in concentration are generally from 2 to 20 times the pre-burn level for the same layer. Relative increases were less in organics from Alligator River and Tetlin than from the Lake States sites.

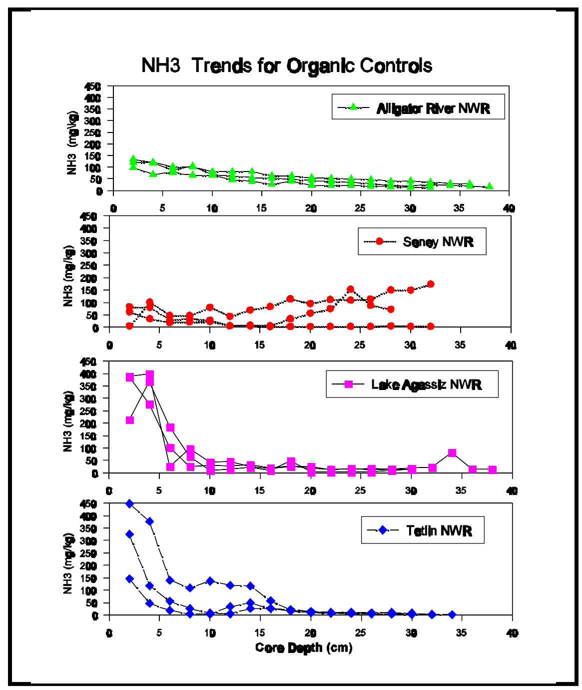

Fig. 20. Comparisons of ammonia concentrations for unburned soils at four organic sites.

PRESCRIBED FIRE AND WILDFIRE ACTIVITIES

The initial intent of the field phases of the project were to test our ignition, smoldering, and heating models and investigate vegetation response for varying burning conditions in actual prescribed burning situations. Our goal was to conduct burning experiments in Alaska, The Lake States, and in North Carolina. In Alaska, at the Tetlin NWR, Larry Van derLinden was planning a prescribed burn in black spruce to improve moose habitat, which we were able to cooperate on. North Carolina pocosin presented a lot of opportunities, but most locations with suitable vegetation are in blocks that are logistically too difficult to burn, because of size, lack of fire breaks and inadequate water control. Smoke issues and the degree of uncertainty of fire behavior predictions in pocosin fuels contribute to the difficulty in locating potential burning sites. Plans for burns on two areas have been developed and will be discussed below. For a variety of reasons we were not successful in working out suitable arrangements for burning experiments in the Lake States.

Fig. 22. Chisana River prescribed fire in Alaska.

CHISANA RIVER PRESCRIBED BURN

Project Description

The Tetlin NWR goal for the Chisana River prescribed burn was to improve wildlife habitat for moose by providing more browse and to regenerate the black spruce stand. On July 17, 1993 Larry ignited the Chisana River prescribed fire (Fig. 22), which was targeted to cover approximately 8,000 acres in black spruce with stringers of white spruce. The purpose of our involvement in the burn was to evaluate the ignition and consumption of the organic layers, document soil heating, and document nutrient changes in relation to organic layer consumption and heating. Because there was no way to achieve water control we could not get contrasting dry and wet treatments. We selected four different conditions within the area that represented what we felt might result in different burning conditions. Much of the ground surface interspersed between black spruce trees was dominated by lichen or feather moss, which we felt would provide a different probability of ignition and thus soil heating than the needle litter surface under the black spruce canopy. The lichen and moss are expected to wet and dry more quickly than the needle litter surface, thus influencing fire spread and behavior. The needle litter under the white spruce canopy had similar characteristics to the black spruce, but was much more extensive and apparently thicker. Tussocks created by Eriophorum (cotton grass) provided yet another surface and condition for fire spread. Some tussocks were used for some aspects of the experiment, but not for the complete range of measurements.

Four spots were selected for each of these surface conditions (and 5 for black spruce) for installation of data loggers and pre-burn and post-burn soil sampling. In addition, we selected 4 tussocks to install data loggers. In all, 21 data loggers were installed for measuring soil temperatures at 8 depths from the ground surface to the frost layer during the burn. Eighteen of the data loggers yielded good temperature data, one partial data, and two failed. Soil samples were collected from L and F layer, the H layer and from the mineral soil before the burn. Post-burn samples were collected from the ash, unburned layer below the ash, unburned H layer (if it was not consumed) and mineral soil. Soil samples were analyzed to identify changes (from pre-burn to post-burn) in pH, organic matter content, nitrogen (total N, NH_3, NO_3), and carbon. Nutrient analyses have been completed, but data summaries and statistical analyses are not complete.

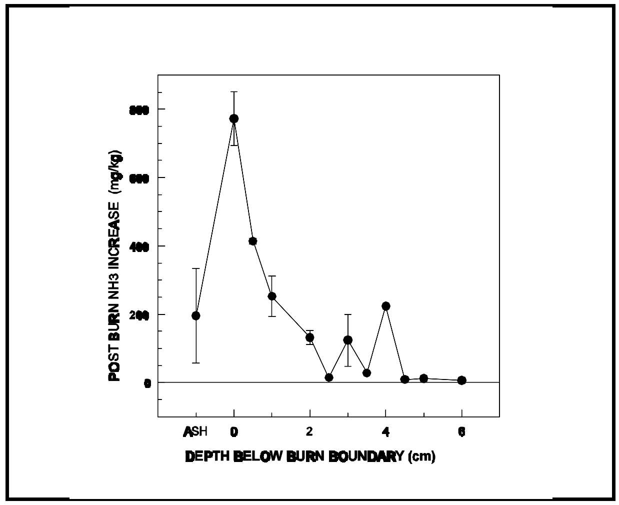

Fig. 23. Postburn increase in NH3 for layers, referenced to the burned/unburned interface, compared to preburn amounts for the same layer. The points are the average and the error bars are the standard deviation.

Preliminary Results

Of the 17 sites, other than tussocks, a portion of the organic layer burned on 14 sites and only the surface litter was consumed on the other 3 sites. Where organic material burned, depth of consumption ranged from 7 to 20 cm and organic matter was consumed down to the mineral soil at 5 sites. All but 2.5 cm of the organic matter was consumed at 50 percent of the sites. Increases in mineral soil temperature were directly related to the amount of residual (unburned) organic material above the mineral soil. Where all organic matter was consumed, mineral soil temperatures exceeded 250 ^{o} C and where very little of the organic layer was consumed, temperatures increased only slightly. Temperatures in the smoldering zone of the organic layers reach a maximum of 600 ^{o} C as the burning front passed a point. While these temperatures are not as high as occur in flaming combustion, temperatures above 50 ^{o} C cause mortality in living tissue and temperatures above 250 ^{o} C begin to effect changes in nutrients. A key feature of the smoldering phase is the long residence times that occur. Temperatures in unburned organic layers and the mineral soil can remain above 100 ^{o} C for periods from 3 to 20 hours.

Preliminary analysis of nutrient changes that occurred in soil layers below the burn boundary, compared to the pre-burn levels, show that available nitrogen (N) in the form of NH_3 increased in a 2.5 cm thick layer immediately below the burn boundary (Figure 23). Increases in the first 0.5 cm layer averaged nearly 800 mg/kg with a standard deviation of 100 mg/kg. At the 2 cm level, increases averaged 150 mg/kg. Some slight and variable increases were noted to a depth of 4 cm. NH_3 levels in the ash average 200 mg/kg higher than the unburned organic material that the ash originated from.

Burning also had an effect on the pH of the layers immediately below the burned boundary. Increases in pH were observed from immediately below the burn boundary to 2.5 cm below the boundary (Figure 24). In the first 0.5 cm layer the pH increased from 1 to 2 units, making the soil less acid (average pH). Increases at the 2.0 to 2.5 cm depth averaged 0.75 units. Some increases were observed below, but the changes were small and variable. Ash pH averaged 8.0

NORTH CAROLINA FIELD STUDIES

The objective of the field efforts in North Carolina was to establish prescribed burning experiments in pocosin vegetation over organic soils to evaluate laboratory developed organic soil ignition and smoldering models, and to study the relationship of different levels of burning on vegetation response. In the process of locating suitable sites for prescribed burning, it became obvious very quickly that there are a number of significant and difficult issues involved in burning in pocosins. Most pocosins and associated plant communities in Eastern North Carolina occur in large relatively undisturbed blocks. These blocks have not been exposed to fire for 30-50 years. The time since the last fire is much longer than the historical fire return interval suggested by a number of fire ecologists. As a result, fuels have accumulated and large intense fires are occurring. Effective fire breaks, either natural or otherwise, do not exist. Additionally, when fire spreads through pocosin, soil conditions are likely to be dry enough to ignite ground fires. Ground fire in organic soil is a fear of fire control and prescribed burners. The occurrence of ground fire poses significant concerns for reburn and escape fire in addition to the considerable smoke problems for long periods. These situations contribute to the complexity and difficulty of conducting prescribed burns in pocosin. This is compounded by the fact that fire spread and behavior in these fuels is not predictable, because of our lack of understanding of the factors that determine the boundary between controllable and uncontrollable fire behavior. The bottom line is, managers feel uncomfortable doing prescribed burns in pocosins.

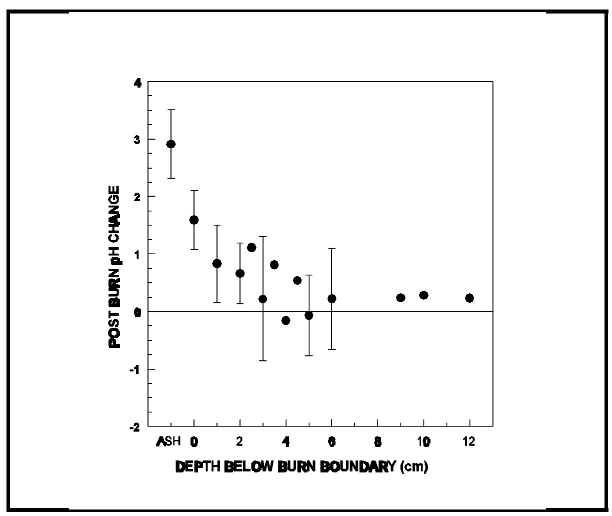

Fig. 24. Postburn pH change for layers, referenced to the burned/unburned interface, compared to pre-burn pH. The points are the average, and the error bars are the standard deviation.

A general strategy was developed to burn small (4 to 10 acre) blocks that are circled by ditches to provide water table control (thus control of soil moisture) and also provide water for fire control. We proposed two burn treatments, a "wet burn" that would consume surface fuels without ground fire, and a "dry burn" that would consume surface fuels and ignite ground fire to consume 1 to 2 feet of peat. An unburned control was included. Two sites were located (at the Croatan National Forest and at the Green Swamp, a Nature Conservancy Preserve) and experimental burn plans have been developed . In addition we took advantage of the opportunity provided by the Fish Day Wildfire in 1994 to sample vegetation response in parts of the fire that experienced different amounts of peat consumption. Unfortunately, we have not been able to complete our planned prescribed burns, except for one unit on the Croatan in June of 1996, but these will be completed when conditions are appropriate for the prescriptions. The following will give a brief description of the plans and results to date.

Croatan National Forest

<u>Catfish Lake Impoundment</u>

The experimental burn units have been established in a large unit of low pocosin located at the northeast corner of the Catfish Lake Waterfowl Impoundment area. The approximately 600 acre block has been v-ditched at 250 foot intervals, but it does not appear that much other disturbance has taken place other than fire. An area at one end of the unit between one of the v-ditches and a canal with a road was chosen for locating the proposed experimental burn units. An experimental plan (Appendix Q) was developed in cooperation with Brad Jenkins (District FMO) for the burning and with Dr. Norm Christensen (Duke University) to sample vegetation and fuels. Our (IFSL) sampling involved soils, ignition, smoldering, and nutrient objectives. Dr. Carl Trettin from the U.S. Forest Service, Center for Forested Wetland Research Lab in Charleston, SC is doing some work with us on carbon resources and peat development at this and other sites. The results of this work will be published when we complete the prescribed burning and data analysis.

Fig. 25. Prescribed fire (June 1996) at Catfish Lake Impoundment in the Croatan National Forest, North Carolina.

Fig. 26. Limited smoldering occurred at the base of this shrub in the Catfish Lake Impoundment prescribed burn. Ignition of the shrub hummock occurred on the side.

On June 23, 1996, the "wet burn" unit was successfully burned. The objective was to obtain a spreading fire that would consume the above ground vegetation and surface fuels, without igniting ground fire. These objectives were met by the crew igniting the sides and using strip head fire across the unit. Ignition was started at 1230 hours with the air temperature at about 94 F, humidity at 62%, and winds at 2 to 3 MPH out of the north-northeast. In some locations a backing fire spread with low flame lengths (1 to 2 feet) that consumed surface needle and shrub litter. Between the head fire strips, fire behavior was more intense, with flame lengths of 6 to 8 feet, and occasional torching of pond pine crowns (Figure 25). In these areas, foliage of the shrubs was completely consumed and most small twigs (<1/4 inch) were consumed. Only a few isolated patches were left unburned within the unit and the fire remained within the burn unit with no spotting outside the unit. By 1500 hours, the fire was out, with the exception of about 20 locations of smoldering at the base of shrubs. By the next day (6/24) only 10 showed any smoke, and by 6/25 we could only find 1 smoke, which went out by the following day. All ignitions of smoldering were very limited in extent (Figure 26) and occurred in the top or sides of shrub hummocks. Overall, the prescribed burn was successful, showing that pocosin vegetation could be burned with acceptable fire behavior to meet desired fuel consumption objectives while maintaining control and avoiding ground fire. Even though the water table was 20 to 24 inches below the surface, the soil moisture was greater than 250 % from 6 inches below the surface to the water table, and a ½ inch of rain 4 days before the burn provided moist conditions (> 150 % MC) below the surface litter to 6 inches below the ground surface. These data will be analyzed in more depth and reported in publication when the other burn is completed.

Fish Day Wildfire: May 1994

The Fish Day Wildfire burned nearly 25,000 acres, much of it in pocosin communities, between 5/21 and 6/2 1994. Since the fire threatened to burn over our experimental sites, we had an opportunity to learn and observe. Some of our observations have already been discussed and are included in a report (Appendix H). The initial fire front and reburns ignited ground fires in several locations that burned and extended suppression and mop up activities into August. In these ground fire areas different amounts of peat consumption were observed, from none to shallow holes burned to 3 to 4 feet of peat consumed. Measurements of soil moisture during the burn at several ground fire sites indicated that ground fire was burning through peat at moisture contents up to 250%.

Five sites with different levels of consumption were located and a cooperative agreement was developed with The Nature Conservancy to monitor vegetation response (plan is in Appendix R). Seven to 10 plots along a transect at each sample location were used to measure fire intensity, soil consumption and burn severity, fuel quantities, species composition, biomass, ground cover, and establish photo points. Vegetation plots used by Dr. Norm Christensen of Duke in a prescribed burning study (1981) were re-established. These plots, with 10 years of vegetation response, were burned again in this fire.

Preliminary results after two post-fire sampling periods show that vegetation response is quite different on the sites. Where deep peat burning occurred, presence and biomass of many of the shrubs was much reduced. Herbaceous plants, some of which occurred in minor pre-burn amounts, dominated the ground cover 1 year after the burn. Sampling is scheduled for at least one more year (fall of 1996) then analyses will be completed and published in cooperation with The Nature Conservancy.

Green Swamp

The Green Swamp Preserve is owned by The Nature Conservancy and is the last remaining undisturbed portion of what was originally called the Green Swamp. A large portion of the preserve is pocosin with deep peat soils. The Nature Conservancy is interested in developing a fire management program in this swamp that includes prescribed burning for the purpose of managing the fuels to reduce the high hazard of wildfire, and maintaining the ecological integrity of the ecosystem. The Nature Conservancy agreed to work with us and provide a site at the Green Swamp that we could use for experimental burning and learning about the effects of burning on the ecosystem.

A group from The Nature Conservancy, the State of North Carolina Division of Forest Resources, the National Resource Conservation Service, Cape Fear Resource Conservation and Development, Federal Paperboard, and the Intermountain Fire Sciences Lab worked closely together to develop a study plan for the burning experiments (Appendix S). The Cape Fear RC&D organization contributed funds toward design and construction of the ditches for the project. This work has involved obtaining a 404 permit from the Corps of Engineers for the ditching. We have worked closely with Jim Sain, the Regional Forester with the North Carolina Division of Forest Resources, and as part of the cooperative effort, they will take the lead in carrying out the prescribed burn in cooperation with Margit Bucher and Linda Gintoli of TNC. As of the summer of 1996, the fire breaks and the ditches have been completed and we are waiting for the appropriate conditions to implement the burn prescription. This cooperative effort and relationship with these groups is an important beginning toward learning together about prescribed burning in pocosin. Completion of this project and future projects will hopefully move the local people in the coastal plain of North Carolina closer toward being able to prescribed burn in pocosin. Results from the Green Swamp project will be reported in subsequent publications and meetings.

MANAGEMENT APPLICATIONS AND CONCLUSIONS

This project provided us, at the Intermountain Fire Sciences Lab, with the resources needed to complete some modeling efforts, extend applications to other ecosystems, allowed us to study fire issues in wetland ecosystems, and make many new contacts. Our working area extends from Alaska to the Lake States to the Southeastern States. As a result, the Fire Effects Project (RWU-4403) at the IFSL has committed some of its resources toward continued research on fire in wetlands in the Southeast. Working relationships have been developed with a variety of groups in North Carolina that are interested in fire in pocosin, particularly with interest in developing safe and ecologically effective prescribed burning programs. The interest in fire issues in pocosin, which is partially due to support provided for this project, has resulted in cooperative working relationships with the North Carolina Forest Service and The Nature Conservancy. A new proposal, submitted to Seymour Johnson Air Force Base, has been funded, which will involve several National Wildlife Refuges, North Carolina Forest Service, The Nature Conservancy, U.S. Forest Service, North Carolina State University, and some other groups to conduct additional research that builds on the results of this project.

During this project we made significant progress in several areas: 1) we have established a much better understanding about conditions required for ignition and burning of duff and organic soil that can be used to develop burn prescriptions and to evaluate the potential for ground fire during suppression activities. 2) A soil heating model was completed and tested in the laboratory for several soils, including organic soils. This model represents our physical understanding of heat transfer processes and predicts soil temperature profiles (temperature changes over time at different depths). 3) Research procedures were developed to measure heat flux under a smoldering fire. These procedures were used to identify factors that influence the fraction of heat that is directed downward into unburned soils. 4) We made significant progress with cooperators in North Carolina in identifying issues in prescribed burning in wetland communities. A number of research and information needs have been identified that are critical to operational prescribed burning programs. 5) Experiments have been initiated that will aid in developing knowledge of specific plant responses in relation to fires of different types, intensities, and severities. A brief summary of these 5 topics will follow.

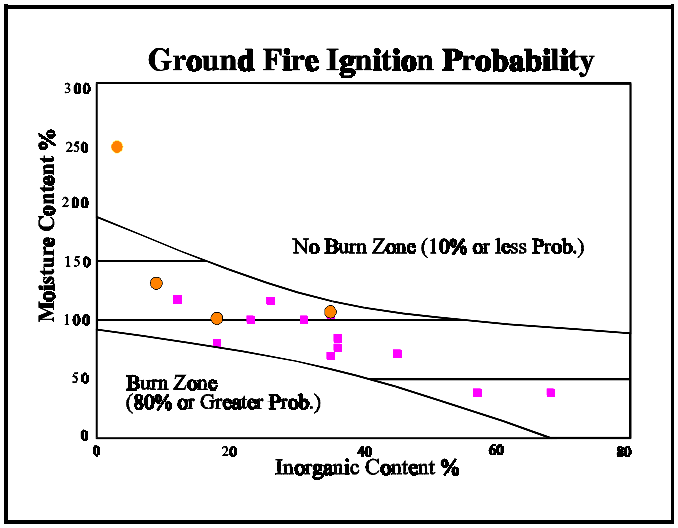

Fig. 27. Ignition probability of organic soils in relation to moisture and inorganic content. Points represent the 50% ignition probability results from ignition tests. The burn and no burn boundaries are the lower and upper 95% confidence lines for the 80% probability of burning and the 90% no burn probability.

IGNITION AND BURNOUT OF DUFF AND ORGANIC SOIL

The consequences of fire igniting ground fire in duff or organic soil are costly in terms of dollars, logistics, smoke, and ecological responses. Consumption of duff or organic soil may be ecologically desirable, or even improve biodiversity, but not as an unexpected event during prescribed burning. We have seen a number of prescribed burning situations that resulted in unexpected ground fires. These occurred, in general, because managers burned over organic layers they thought were too wet to burn. These burns resulted in unexpected ground fire. In fairness to prescribed burners, however, we find that the literature on the subject is somewhat confusing, and indicates, for example, that organics will ignite at a wide range of moisture contents (see table 1 on page 8).

When burning on organic soils, it is especially important to know the moisture content of the lower litter layer and the organic soil. Moisture and inorganic content are key factors that influence ignition. If a spreading fire encounters dry soil or dries the moist surface layer of the peat, the organic soil will ignite. Figure 27 summarizes the results discussed earlier and adds some other probability lines for ignition. This graph includes results for organic material of all types and from all locations that we tested. Organic soils will ignite with a greater than 80 percent probability at moisture contents up to 90 percent for soils with organic contents above 90 percent. As inorganic content increases, soils must be drier for ignition to occur. Over the range of inorganic contents we sampled, there is a 10 percent probability that ignition will occur at moisture contents from 90 to 190 percent. With the exception of one point (inorganic content 5 % and MC

250 %) all our tests fell in the above range. The outlying point represents peat soils collected from pocosin in eastern North Carolina. This suggests that ignition on these soils can occur at much higher moisture contents than other organic soils that we tested.

Observations in the field and laboratory experiments burning undisturbed cores confirm these results. Once organic soil has been ignited, a ground fire can spread and sustain itself at moisture contents up to 250 percent. In our only attempt, to date, of prescribed burning in pocosin, the surface litter layer (moisture contents of 20 to 30 %) carried the fire and were consumed. Moisture contents of material immediately under the 1 inch layer of litter were from 180 to 250 %, and were greater than 250 % in the 0 to 6 inch layer. These layers did not ignite and no ground fire ignition occurred. The hummock/depression relief that occurs in pocosin is also important in the ignition process. Shrubs and old pine stumps usually form the hummocks, which can be as much as 19 inches higher than the depressions. Litter amounts are greater on hummocks and conditions (moisture, fuel to volume) are more favorable for ignition. The partially decayed wood of pine stumps are especially susceptible to ignition and initiating ground fire. Fuel on hummocks is less influenced by the water table and more connected to the current weather conditions than fuel in depressions. It is expected that ignitions on hummocks are more likely to develop into ground fires. In the Catfish Lake Impoundment burn, ignition was observed on the side, or top, of about 25 hummocks. Within two days these self-extinguished, probably because the moisture contents were above 250 % or greater at soil depths greater than 2 inches, and the site received about 0.5 inches of rain two days after the burn.

Initial results and understanding about ignition and consumption of organic soils and duff have been included in FOFEM for pocosin. The amount of organic soil consumption depends on the soil moisture content, water table depth, and the number of days since rain. The Catfish Lake Impoundment prescribed burn at the Croatan confirmed these ideas, but we need a strong validation effort using additional prescribed burns in peat soils and with duff to improve calculations for soil and duff consumption in FOFEM. We plan to complete our planned prescribed burns on the Croatan NF and at the Green Swamp with The Nature Conservancy.

HEAT FLUX AND SOIL HEAT TRANSFER

A model to simulate heat transfer in soils and predict soil temperature profiles over time at different depths has been developed, evaluated independently, and undergone initial testing in the laboratory. This model, developed by Dr. Gaylon Campbell and others, with support from this project does a good job of representing the important processes of heat transfer in a soil media. Several publications (see Appendices C,D,E, and G) report on the detail of the model and the initial testing. In laboratory testing conducted on several soils, including organic soils, simulated temperature profiles duplicate the experimentally observed profiles quite closely (Figures 15,17, 18, and 19). We have also measured temperatures in prescribed burns, using data loggers developed during this project. Model comparisons to compare simulated soil temperatures with observed soil temperatures will be made in the near future. Future prescribed burns will also be used to test the model.

Currently the soil heat transfer model is a research model, requiring inputs to run that are not easily available to managers. Our goal is to "empiricize" the model so it will operate with inputs that are available to managers. To accomplish this, we need to develop linkages between soil types and their physical characteristics. The empiricized version of the model will be included in FOFEM.

A stirred water calorimeter heat flux sensor was developed to measure heat flowing in a downward direction from smoldering fires. This sensor was tested and used to measure heat loads (heat per unit area) under burning beds of peat with different physical properties. Results showed an erratic variation of heat flux with time, but this could be smoothed to provide a characteristic peak and shape of distribution and calculate a characteristic heat load. Heat load beneath a bed increases with depth of the bed and increased bulk density. In other words, as the amount of material in a space increases, the amount of heat beneath the material is greater. Moisture and inorganic content also influences heat load.

The efficiency of the smoldering process is surprising. Measurements indicate that 40 to 73 percent of the heat released in the smoldering process is measured under the fuel bed. This means that a high percentage of the heat from a smoldering fire is available for heating the soil underneath. This is somewhat surprising, since we would have expected more heat loss from an open smoldering peat bed. The literature indicates that efficiencies for a surface fire are much less, typically in the range of 8 to 15 percent and in the extreme up to 25 percent.

Since we now have a good heat soil heat transfer model and techniques for measuring heat flux and heat load, we need to use these tools to couple the production of heat and transfer of heat. A model is needed to simulate heat flux underneath fires of different types (surface fires, ground fires) to provide the boundary condition input for the soil heat transfer model. This is a major research need for the future.

PRESCRIBED BURNING ISSUES

During the course of this project we have had contacts with many scientists and managers to discuss issues in prescribed burning in wetlands, and have had the opportunity to view wildfires and participate in prescribed burning. We also had the opportunity of presenting papers (Appendix B and N) at the 19th Tall Timbers Fire Ecology Conference in 1993 and the Southern Forested Wetlands Ecology and Management Conference in 1996. Although we found a great deal of interest in Alaska and the Lake States regarding our project work, we found the greatest interest and support in the Southeast. This is not surprising, because folks in the Southeast have a long history in prescribed burning and probably the largest window of opportunity for burning. While prescribed burning is a commonly used tool, the issues surrounding fire in pocosin are quite complex. The concern with ground fire and the lack of understanding about initiation of ground fire, sustained ground fire, smoke production, and etc., is the root of much concern and uncertainty, both for wildfire and prescribed fire situations. Although, more testing needs to be done, and management models need to be developed, we feel that we have the research results needed to help managers develop a level understanding of the problem.

A major concern with fire in pocosin, identified during this project, is related to fuels, flammability, and hydrology. It is not clear under what conditions a prescribed fire will carry through the fuels and yet remain controllable. Many fire managers feel that either fire won't carry at all or it will race out of control, such that no control lines will contain the spread. In their experience, existing fuel models do not explain observed fire behavior. As a result, great concern and uncertainty exists about conducting prescribed burns in these types of fuels. Much research is needed to determine under what conditions, if any, prescribed burns can be safely conducted to meet fire management and ecological objectives.

In cooperation with the Croatan NF, TNC, and the State of North Carolina Division of Forestry, we have developed prescribed burning plans for several experimental burns that will address some of the questions and concerns. One prescribed burn has been completed and the data are being analyzed. The others will be completed when the weather cooperates. In addition, we have been funded by Seymour Johnson Air Force Base to research issues about fuel, flammability, hydrology, and soil conditions that will help them to develop a prescribed burning program at the Dare County Air Force Bomb Range. During the course of this project we hope to conduct several experimental burns to test our ideas and use as demonstrations.

Fig. 28. Open grassland savannah 8 years after fire consumed 3 to 4 feet of the organic soil. The pre-fire plant community was a dense pond pine shrub community.

PLANT RESPONSE

The literature and our personal observations indicate that different amounts of organic soil consumption cause different plant responses and can lead to significant changes in the plant community. Knowledge about specific plant species responses are limited in wetland ecosystems and are particularly limited with respect to fire. Observations in old burns indicate that dense shrub communities can be converted to open grassland savannahs when significant amounts of soil consumption occur (Fig. 28). We were able to take advantage of the Fish Day Wild Fire in the Croatan NF, to establish vegetation plots in areas with differing amounts of soil consumption. Two post-burn measurements have been made so far and a third will be made in the fall of 1996. Hopefully, we can continue these measurements for a few more years. Preliminary data from a low pocosin shrub community show a change from a shrub community to a grassland community where 1.5 to 2 feet of soil was consumed (Fig. 29).

Fig. 29. A dense stand of grass (Broomsedge) 1 year following the Fish Day Fire. Eighteen to twenty-four inches of organic soil was consumed. The pre-fire community was dense low shrub pocosin.

Vegetation plots have been established on our experimental prescribed burns site. These plots will be used to monitor the changes that occur as a result of the burning treatment. Additional plant response studies are included as part of the project with Seymour Johnson Air Force Base. Laboratory studies are needed to provide information about how underground plant parts respond to different levels of heating at different seasons and phenological stages.

Before we implement prescribed fire to manage ecological processes in pocosin, assuming that this will be possible, we also need much information about soil processes. Research is needed to understand peat accumulation and decomposition rates and to characterize the carbon resources in wetland soils. We also need to ask questions about nutrient quality of different wetland communities and how fire treatment influences subsequent community response. These, and other issues need to be addressed so research models can be integrated into management models to help manage these ecosystems to sustain the ecosystem processes.

LITERATURE CITED

Albini, F., M.R. Amin, R.D. Hungerford, W.H. Frandsen, and K.C. Ryan. 1996. Models for fire-driven heat and moisture transport in soils. General Technical Report INT-GTR-335, 16 pgs.

Artsybashev, E.S. 1983. Forest fires and their control. Lesnaya Promyshlennost' Publishers, Moscow.

Aston, A.R. and A.M. Gill. 1976. Coupled soil moisture, heat and water vapor transfers under simulated fire conditions. Australian Journal of Soil Research 14:55-66.

Brown, J.K., M.A. Marsden, K.C. Ryan, and E.D. Reinhardt. 1985. Predicting duff and woody fuel consumption in the Northern Rocky Mountains. USDA For. Serv. Res. Pap. INT-337. 23 p.

Bancroft, L. 1976. Fire Management in Everglades National Park. Fire Management 37:18-21.

Campbell, G.S., J.D. Jungbauer, Jr., S. Shiozawa, and R.D. Hungerford. 1993. A one-parameter equation for water sorption isotherms of soils. Soil Science 156 (5): 302-305.

Campbell, G.S., J.D. Jungbauer, Jr., W.R. Bidlake, and R.D. Hungerford. 1994. Predicting the effect of temperature on soil thermal conductivity. Soil Science 158 (5): 307-313.

Campbell, G.S., J.D. Jungbauer, Jr., K.L. Bristow, and R.D. Hungerford. 1995. Soil temperature and water content beneath a surface fire. Soil Science 159 (6): 363-374.

Christensen, N.L. 1981. Fire regimes in southeastern ecosystems. P. 112-136 in H.A. Mooney, T.M. Bonnicksen, N.L. Christensen, J.E. Lotan, and W.A. Reiners, eds. Fire regimes and ecosystem properties. USDA For. Serv. Gen. Tech. Rep. W0-26.

Christensen, Norman L., Rebecca Bea Burchell, Annette Liggett, and Ellen Simms. 1981. The structure and development of pocosin vegetation. Pages 43-61 in C.J Richardson, ed. Pocosin wetlands: an integrated analysis of Coastal Plain freshwater bogs in North Carolina. Hutchinson Ross Publishing Co., Stroudsburg, PA.

Cypert, E. 1961. The effects of fires in the Okefenokee Swamp in 1954 and 1955. The American Midland Naturalist 66(2):485-503.

Cypert, E. 1973. Plant Succession on burned areas in Okefenokee Swamp following the fires of 1954 and 1955. In: Proceedings, Annual Tall Timbers Fire Ecology Conference 12:199-217.

DeBano, L.F. 1981. Water repellent soils: a state-of-the-art. General Technical Report PSW-46. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.

Ellery, W.N., K. Ellerym, T.S. McCarthy, B.Cairncross, and R. Oelofse. 1989. A peat fire in the Okavango Delta, Botswana, and its importance as an ecosystem process. African Journal of Ecology 27:7-21.

Frandsen, W.H. 1991. Heat evolved from smoldering peat. International Journal of Wildland Fire 1:197-204.

Frandsen, W.H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. Can. J. For. Res. 17:1540-1544.

Frost, C. 1995. Presettlement fire regimes in southeastern marshes, peatlands and swamps. Tall Timbers Fire Ecology Conference No. 19, November 3-6, 1993.

Gilliam, J.W. 1991. Wet soils in the North Carolina lower coastal plain. Wetlands 11 (special issue):391-398.

Harrington, M.G. 1987. Predicting reduction of natural fuels by prescribed burning under ponderosa pine in southwestern Arizona. USDA For. Serv. Res. Note RM-472. 4 p.

Hartford, R.A. 1989. Smoldering combustion limits in peat as influenced by moisture, mineral content, and organic bulk density. Pages 282-286 in D.C. MacIver, H. Auld, and R. Whitewood, eds. Proceedings of the 10th Conference on Fire and Forest Meteorology, 1989 April 17-21, Ottawa, Ontario. Forestry Canada, Petawawa National Forestry Institute, Chalk River, Ontario.

Hawkes, B.C. 1993. Factors that influence peat consumption under dependent burning conditions: a laboratory study. PhD thesis, Univ. of Montana. 155 p.

Heinselman, M.L. 1981. Fire intensity and frequency as factors in the distribution and structure of northern ecosystems. Pages 7-57 in H.A. Mooney, T.M. Bonnicksen, N.L. Christensen, J.E. Lotan, and W.A. Reiners, technical coordinators. Fire regimes and ecosystem properties: conference proceedings. General Technical Report WO-26, U.S. Department of Agriculture Forest Service, Washington D.C.

Hermann, S.M., R.A. Phernetton, A. Carter, and T. Gooch. 1991. Fire and vegetation in peat-based marshes of the coastal plain: examples from the Okefenokee and Great Dismal Swamps. Pages 217-234 in Proceedings of 17th Tall Timbers Fire Ecology Conference. High intensity fire in wildlands: management challenges and options. Tall Timbers Research Station, Tallahassee, Florida.

Johnson, E.A. 1992. Fire and vegetation dynamics: studies from the North American boreal forest. Cambridge University Press, New York.

Little, S.N., R.D. Ottmar, and J. Ohmann. 1986. Predicting duff consumption from prescribed burns on conifer clearcuts in western Washington and western Oregon. USDA For. Serv. Res. Pap. PNW-362. 29 p.

McMahon, C.K., D. Wade, and S. Tsoukalas. 1980. Combustion characteristics and emissions from burning organic soils. USDA Rep. 80-15.5. 16 p.

Norum, R.A. 1977. Preliminary guidelines for prescribed burning under standing timber in western larch/Douglas-fir forests. USDA For. Serv. Res. Note INT-229. 15 p.

Otte, L.J. 1981. Origin, development and maintenance of pocosin wetlands of North Carolina. Unpublished report to the North Carolina Natural Heritage Program. North Carolina Department of Natural Resources and Community Development, Raleigh, North Carolina.

Ottmar, R.D., S.N. Little, and J. Ohmann. 1985. Predicting duff reduction to reduce smoke from clearcut slash burns in western Washington and western Oregon. P. 139-144 in Proceedings, 8th AMS/SAF Conference on Fire and Forest Meteorology, Am. Met. Soc. Detroit.

Peter, S. 1992. Heat transfer in soils beneath a spreading fire. Doctoral dissertation, University of New Brunswick, Fredericton, New Brunswick, Canada. 479 p.

Reinhardt, E.D., R.E. Keane, J.K. Brown, and D.L. Turner. 1991. Duff consumption from prescribed fire in the U. S. and Canada: a broadly based empirical approach. P. 362-370 in Proceedings, 11th Conference of Fire and Forest Meteorology, Missoula, MT, April 16-19, 1991. Soc. Am. For., Bethesda, MD.

Richardson, C.J. 1991. Pocosins: an ecological perspective. Wetlands 11 (special issue):335-354.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service Research Paper. INT-115, 40p, illus.

Schafale. Michael P. And Alan S. Weakly. 1990. Classification of the natural communities of North Carolina: third approximation. North Carolina Natural Heritage Program, Division of Parks and Recreation, N.C. Department of Environment, Health and Natural Resources. 325 pgs.

Shafizadeh, F. and W.F. DeGroot. 1976. Combustion charactersitics of cellulosic fuels. In: The uses and properties of carbohydrates and lignins. Eds: F. Shafizadeh, K.V. Sarkanen and D.A. Tillman. Academic Press, New York.

Shearer, R.C. 1975. Seedbed characteristics in western larch forests after prescribed burning. USDA For. Serv. Res. Pap. INT-167. 26 p.

Wade, D., J. Ewel, and R. Hofstetter. 1980. Fire in south Florida ecosystems. USDA For. Serv. Gen. Tech. Rep. SE-17. 125 p.

Ward, D.E. 1990. Factors influencing the emissions of gases and particulate matter from biomass burning. Pages 418-436 in J.G. Goldammer, ed. Fire in the tropical biota. Springer-Verlag, Berlin.

Weakley, A.S. and M.P. Schafale. 1991. Classification of pocosins of the Carolina coastal plain. Wetlands (special issue): 355-375.

Wein, R.W. 1983. Fire behavior and ecological effects in organic terrain. P. 81-96 in R.W. Wein and D.A. Maclean, eds. The role of fire in northern circumpolar ecosystems--scientific committee on problems of the environment (Scope) 18. John Wiley and Sons LTD, Chichester, England.

CONTENT OF APPENDICES

Appendix A - Hungerford, R.D., K.C. Ryan, and J.J. Reardon. 1994. Duff consumption: new insights from laboratory burning. Proceedings of the 12th Conference on Fire and Forest Meteorology, pgs 472-476.

Appendix B - Hungerford, R.D., W.H. Frandsen, and K.C. Ryan. 1995. Ignition and burning characteristics of organic soils. Proceedings of the Tall Timbers Fire Ecology Conference No. 19, November 3-6, 1993, pgs 78-91.

Appendix C - Campbell, G.S., J.D. Jungbauer, Jr., S. Shiozawa, and R.D. Hungerford. 1993. A one-parameter equation for water sorption isotherms of soils. Soil Science 156 (5): 302-305.

Appendix D - Campbell, G.S., J.D. Jungbauer, Jr., W.R. Bidlake, and R.D. Hungerford. 1994. Predicting the effect of temperature on soil thermal conductivity. Soil Science 158 (5): 307-313.

Appendix E - Campbell, G.S., J.D. Jungbauer, Jr., K.L. Bristow, and R.D. Hungerford. 1995. Soil temperature and water content beneath a surface fire. Soil Science 159 (6): 363-374.

Appendix F - Campbell, G.S. 1994. Simulation of soil heating under smoldering duff fires. Report prepared for the Intermountain Fire Sciences Laboratory, 23 pgs.

Appendix G - Albini, F., M.R. Amin, R.D. Hungerford, W.H. Frandsen, and K.C. Ryan. 1996. Models for fire-driven heat and moisture transport in soils. General Technical Report INT-GTR-335, 16 pgs.

Appendix H - Hungerford, R.D., K.C. Ryan, and J. Reardon. 1994. Fish day fire (Croatan National Forest) notes. Intermountain Research Station, 7 pgs.

Appendix I - Frandsen, W.H. 1996. Ignition probability of organic soil. Draft manuscript.

Appendix J - Schneller, M. and W. Frandsen. 1996. A stirred water calorimeter for measuring heat flux from smoldering combustion. Draft manuscript.

Appendix K - Frandsen, William. 1996. Heat flow measurements from smoldering porous fuel. Draft manuscript.

Appendix L - Peter, Selvin. 1996. Development of a heat flux model software adaptation to run on an IBM compatible PC software. Intermountain Fire Sciences Cooperative Report.

Appendix M- Amin, M.R., and F.A. Albini. 1995. An analytical and numerical investigation of heat transfer in fire-heated soils. Intermountain Research Station final report for INT-94968-RJVA, 30 pgs.

Appendix N - Hungerford, R.D., and K.C. Ryan. 1996. Prescribed fire considerations in southern forested wetlands. Proceedings of the Southern Forested Wetlands Ecology and Management Conference, Clemson University, pgs 87-92.

Appendix O- Balatsos, Panayiotis C. 1994. Pyrogenic heat flow into soil and heat-induced tissue damage of Agropyron Spicatum during simulated fire. PhD. Dissertation, University of Idaho.

Appendix P - Hungerford, R.D. Study Plan for laboratory study objectives 4 and 5.

Appendix Q - Hungerford, R.D. Study plan for experimental peat burn treatments at Croatan. DOI study RWU-4403-127: Addendum 3.

Appendix R - Hungerford, R.D. Croatan/Fish Day fire - post fire monitoring plan. DOI study RWU-4403-127: Addendum 5.

Appendix S - Hungerford, R.D. Green Swamp burning experiments: draft study plan. North Carolina Nature Conservancy, North Carolina Forest Service, and U.S. Forest Service, Intermountain Fire Sciences Lab.