PRESCRIBED FIRE BEHAVIOR AND CUSTOM FUEL MODELING IN THE PITCH PINE-SCRUB OAK BARRENS AND PINE-OAK FORESTS OF NEW ENGLAND

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by

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Abstract

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Rates of spread and fuel consumption were measured during five prescribed fires in southern and central coastal New England pitch pine-scrub oak barrens and pine-oak forests (at Martha'a Vineyard and Truro, Massachusetts, and at Hollis, Maine). Observed rates of spread and fireline intensities (Byram's intensity) were compared with predicted values using standard fuel models and the fire behavior prediction program BEHAVE. None of the thirteen standard fuel models for predicting fire behavior accurately represent fire behavior in the pitch pine-scrub oak barrens and pine-oak forests of New England. More accurate, site-specific custom fuel models were developed using the FUEL subsystem of BEHAVE. Fuel bed characteristics must be adjusted to account for fuel bed heterogeneity and the volatile species found in these fuel types. Correction factors for fuel depth and vegetative cover are presented as a guide for fire managers who wish to develop more accurate models for similar fuel types. Site specific fuel models are a valuable tool for land managers and prescribed fire practitioners involved with the restoration and maintenance of pitch pine-scrub oak and pine-oak communities.

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Introduction

There is a need for a means to accurately predict fire behavior during the dormant and growing seasons in northeastern pitch pine (*Pinus rigida*) - scrub oak (*Quercus spp.*) barrens (Patterson and White 1993). In today's fragmented and highly populated New England landscape, historical sources of ignition have been diminished, and uncontrolled wildfires are intolerable, yet ultimately unavoidable. From both wildfire prevention and conservation perspectives, prescribed fire is a valuable land management tool and an integral component of an active fire management program. However, current fire behavior prediction fuel models have not been adopted to barrens fuel types. Public land management agencies and private conservation organizations have an interest in using prescribed fire to restore and conserve New England's remnant pitch pine-scrub oak barrens, because many endangered and threatened species are associated with barrens communities (Forman 1979, Patterson and White 1993).

During the dormant season, fires in pitch pine-scrub oak (PP-SO) barrens can burn with high intensity. Flame lengths of 40 m and consumption rates of 10 ha/min have been observed (Patterson and White 1993). High-intensity fire behavior presents control problems and is an obstacle to state and private agencies trying to use prescribed fire to achieve resource management objectives. Growing-season fires in barrens fuel types are less intense and move more slowly than dormant-season fires, but still burn with high intensity. Drought conditions during the growing season allow for severe burns which consume duff, burn out root systems, and expose mineral soil necessary for the establishment of many barrens species (Patterson and White 1993). Because of the high intensity of prescribed fires in PP-SO barrens, accurate fire behavior prediction is essential to the planning, scheduling, and execution of safe and effective prescribed burns.

PP-SO barrens are a fire maintained and fire dependent community (see Natural Community Fact Sheet, Appendix A). They are characterized by a widely scattered canopy of pitch pine, a multi-level shrub layer, a herbaceous layer, and a litter layer. The shrub layer is often composed of high and low shrubs. High shrubs include scrub oaks and huckleberry (*Gaylussacia baccata*), and low shrubs include blueberry (*Vaccinium angustifolium* and *V. vacillans*). The ericaceous foliage of huckleberry contains volatile oils which allow green leaves to burn very hot and vigorously and serve as dangerous ladder fuels (Crary 1986). An herbaceous layer is present in areas with sufficient sun exposure. Pennsylvania sedge (*Caryx pennsylvanica*), wintergreen (*Gaultheria procumbens*), mayflower (*Epigea repens*), and cow-wheat (*Melapyrum lineare*) are among the species present in the herbaceous layer. Where abundant, these species contribute to the volatility of surface fuels in the dormant season.

This study examined prescribed fire behavior in northeastern PP-SO barrens. Prescribed fires were conducted and careful field measurements were taken in the PP-SO barrens and pitch pine-oak forests of the Manuel F. Correllus State Forest on Martha's Vineyard, Massachusetts, the Maine Army National Guard Base in Hollis, Maine, and the Cape Cod National Seashore, Massachusetts. The specific objectives of the study were as follows:

1. Determine the amount of fuel consumed in prescribed fires
2. Calculate the fireline intensity and rate of spread for each fire
3. Develop a site-specific fuel model for each site
4. Compare the fire behavior predictions of custom models with observed fire behavior and fire behavior predicted by standard fuel models.

Literature Review

Modern fire behavior prediction in the United States is based upon Rothermal's fire model (1972), which estimates fire behavior parameters in the flaming front of a surface fire based upon fuels, weather, and slope. Rothermal's mathematical model of fire spread is the foundation of the Fire Behavior Prediction System (FBPS) (Rothermal 1983; Burgan and Rothermal 1984; Andrews 1986; Andrews and Chase 1989). The FBPS estimates fireline intensity, reaction intensity, heat per unit area, rate of spread, and flame length of the flaming front of a surface fire in uniform fuels as controlled by fuels, weather, and topography (Figure 1). Predictions are independent of source of ignition and other nearby fires. Rothermal's fire model has been successfully field tested in many fuel types (Figure 2). The FBPS has been adapted for use with nomograms, the Hewlett Packard HP 71-B calculator, and the personal computer.

Fuel conditions are represented by one of the 13 Northern Forest Fire Laboratory (NFFL) fuel models (Anderson 1982) (Figure 3) or by user-created custom fuel models. A fuel model is a numerical characterization of a fuel complex to be entered in a set of equations for predicting fire behavior parameters (Rothermal 1972). Fuel models are determined by the fuel type that carries the fire (grass, shrub, timber litter, and slash), fuel load (kg/ha) for live fuel and for three size classes of dead woody fuel (1 hr, 10 hr, and 100 hr), the surface area to volume ratio (m^2/m^3) of each size class, fuel bed depth (m), packing ratio, and the moisture of extinction for dead fine fuels (Anderson 1982). Although the 13 NFFL fuel models categorize most fuel types encountered in the United States, none accurately represent fire behavior in pitch pine/scrub oak barrens of New

England (Patterson and White 1993; Patterson, 1998). NFFL fuel models numbers 4 (chaparral), 6 (dormant brush / hardwood slash), and 7 (Southern rough) have been used to estimate fire behavior in barrens fuel types, but seriously over-estimate (fuel model 4) or under-estimate (fuel models 6 and 7) the rate of spread and/or fireline intensity, as will be demonstrated in this study.

BEHAVE

The FBPS has been adopted for use on personal computers in the form of BEHAVE, a suite of interactive computer programs used to predict fire behavior based on user-defined inputs for fuels, weather, and topography. The BEHAVE system of fuel modeling and fire prediction programs was developed in the 1980s and is widely used by fire practitioners as an aid in planning the containment and control of prescribed and wildland fires as well as predicting their ecological consequences. The mechanics and equations used by BEHAVE are explained in detail by Dell'Orfano (1996).

BEHAVE is divided into two subsystems: BURN (Andrews 1986, Andrews and Chase 1989) and FUEL (Burgan and Rothermal 1984)(Figure 4). The BURN subsystem contains the prediction programs FIRE1 and FIRE2 and is used in conjunction with one of the NFFL fuel models or a custom model for predicting fire behavior. The fuel modeling subsystem (FUEL) is used for constructing custom, site-specific fuel models when none of the 13 NFFL models is appropriate (e.g. the pitch pine/scrub oak barrens of New England) (Salazar 1985, McCaw 1991). The FUEL subsystem is composed of the programs

NEWMDL (for making custom models) and TSTMDL (for testing those custom models against field observations).

Custom fuel models can be constructed as static or dynamic models, depending on the presence of live fuels. Static models are created for sites without live fuels (dormant season) or for sites where live fuels do not significantly influence fire behavior. Dynamic models consider live fuels and their effects on fire behavior (e.g.. lower rates of spread). For this research project, static models were created for the Martha's Vineyard and Cape Cod National Seashore study sites, and a dynamic model was created for the study site in Hollis, ME.

Fire Behavior Measurements

Custom fuel models must be tested against field measurements before they can be used in the practice of predicting fire behavior (Burgan and Rothermal 1984). The two most important dynamic properties of the wildland fire flaming front are rate of spread and fireline intensity (Pyne 1984). Fireline intensity is the standard variable measured in the study of fire behavior and fire ecology (Moore et al. in prep.). Fireline intensity is a measure of the energy release rate per linear length of flaming front per unit time (kW/m/s) and is directly related to flame length (Rothermal and Deeming 1980). Byram (1959) significantly advanced fire behavior prediction when he introduced an equation for calculating fireline intensity as the product of the heat value of the fuel, the dry weight of the fuel consumed, and the rate of spread. "Byram's intensity" is expressed as:

$$I = HWR$$

where: I = fireline intensity (kW/m/s)
H = heat content (kJ/kg)
W = dry weight of fuel consumed by the flaming front (kg/m²)
R = rate of spread (m/s)

The variables in this equation can either be measured or estimated. All of the 13 NFFL standard fuel models use 18,605 kJ/kg (8,000 Btu/lb) for heat content (BEHAVE accepts values from 7,000 to 10,000 Btu/lb). This is accepted as a standard value for wildland fuels. Heat content in PP-SO fuels has not been directly measured (Dell'Orfano 1996). It is likely that the heat content of a fuel complex varies with season and the presence of foliage. Sensitivity analysis conducted by Dell'Orfano (1996) shows that varying heat content values has a predictable effect on the estimation of fire behavior parameters, most notably in rate of spread predictions. As heat content increases, rate of spread increases. For this research, heat content has been held constant for dead fuels (18,605 kJ/kg / 8,000 Btu/lb) and live fuels (20,930 kJ/kg / 9,000 Btu/lb), based upon recommendations in Burgan and Rothermal (1984).

Careful field sampling of pre- and post-fire fuel loading can produce good estimates of the dry weight of fuels consumed by the flaming front. When compared with values generated by Byram's equation for fireline intensity, this value can be inflated by substantial amounts of glowing phase combustion (smoldering) (Finney and Martin 1992). However, the prescribed fires conducted for the purposes of this research did not, with one exception, show substantial amounts of smoldering of surface fuels.

Measuring rate of spread is difficult, because fires are transient and occur under difficult conditions (Gill and Knight 1991). Due to the intense nature of fire in barrens fuel types, first-hand observation of fire behavior, even in controlled burns, is often impractical and/or unreliable (Patterson and White 1993). Australian fire scientists have developed new techniques of electronic data collection using heat sensing thermocouples. These have proven effective for measuring fire behavior over space and time (Moore et al. in prep.). The Temperature-Residence-Time Meter (TRTM) is an instrument which measures the length of time registered by a thermocouple above approximately 200°C - the temperature used to indicate the presence of flames. TRTMs are used to measure residence time and rate of spread. The TRTM consists of a plastic box containing a digital stopwatch and electronic circuits. A detachable thermocouple is attached to the box. The box is buried in soil with the thermocouple exposed 5 to 10cm above ground. The TRTM records the time of flame arrival and departure at the thermocouple. Rate of spread can be measured by synchronizing and burying several TRTMs in a systematic pattern inside a burn unit.

My research project used this Australian technology to measure rates of spread in PP-SO barrens and pine-oak forests. With good estimates of fuel consumption and rates of spread, calculating fireline intensity using Byram's equation is facilitated.

Study Sites

Study sites were located in the pitch pine-scrub oak barrens of the Manuel F. Correllus State Forest on Martha's Vineyard, Massachusetts and the Maine Army National Guard Base in Hollis, Maine; and the pitch pine-oak forests of the Cape Cod National Seashore, Massachusetts (Figure 5). A brief description of each study site follows.

Manuel F. Correllus State Forest on Martha's Vineyard, Massachusetts

The study site is characterized by classic coastal plain scrub oak barrens vegetation with a very dense scrub oak (up to 2-3 meters tall) / huckleberry (approximately one meter tall) high-shrub cover layer and scattered small patches of open heathland and grassland. Tree oaks and isolated pines were widely scattered and did not contribute to fire behavior.

The research burn was conducted on June 12, 1996 in an approximately 2 hectare (5 acres) burn unit. The scrub oak was just beginning to leaf out. There was minimal live fuel present at the time of the burn due to several frosts in late spring, 1996. Late frosts and recent gypsy moth infestations left a significant amount of standing dead fuel on the site. This dead fuel was lightly draped with lichens.

Maine Army National Guard Base in Hollis, Maine

The barrens in Maine and New Hampshire have been classified as a "boreal variant" of the pitch pine-scrub oak community and are distinguished by the presence of characteristically northern plant species (Schweitzer and Rawinski 1988). The study site in Hollis has greater than 30% cover of pitch pine, at least 40% scrub oak and less than 25% gray birch. The herbaceous layer is dominated by blueberry, with bracken fern (Pteridium aquilinum) as a frequent sub-dominant (Patterson 1997). Little huckleberry occurs at this site.

Hollis has the most mesic site conditions of the three study sites. The presence of gray birch and lack of huckleberry distinguishes this barrens area from the others I studied. Lush herbaceous plants like bracken fern and Pennsylvania sedge (Caryx pennsylvanica) were green and plentiful in the herbaceous layer, and blueberry and scrub oak had leafed-out at the time of the burns, which were conducted on June 23, 1995 (Unit I-A) and July 12, 1996 (Unit II-E). Unit "I-A" is 1 hectare (2.5 acres) and unit "II-E" is 1.8 hectares (4.4 acres).

Cape Cod National Seashore, Massachusetts

The Cape Cod National Seashore site is located in South Truro, MA and has been the site of long-term fire effects research conducted by William A. Patterson III. The two fires used for this research project were each conducted in one hectare plots (TP01 and TP06) that had not burned for at least 50 years. The study area is a coastal pitch pine - tree oak forest with a dense shrub layer of huckleberry ranging from 0.6 to 1.5 meters in height (Crary 1986; Patterson 1988). Although not "barrens", coastal pine-oak forests have many species in common with the other barrens (i.e. huckleberry, pitch pine, scrub oak, and blueberries). Pitch pine - oak forests occur on similarly xeric sandy soils, and represent similar wildfire hazards.

The research burns at the Cape Cod National Seashore were conducted on August 4, 1995 and July 22, 1996 in plots TP01 and TP06, respectively. Fire behavior in most of plot TP06 was under the influence of a seven percent slope, whereas all other study sites were on nearly level ground.

Methods

Information on fuels, weather, and topography are the input parameters required by the FBPS and were documented at each of three study sites. Variables were recorded in the field prior to, during, and after the execution of the prescribed fires. Fuels at the Cape Cod National Seashore study site were extensively sampled in the 1980s by Patterson and Crary (unpublished data).

Fuels

The preburn fuel loading was estimated by destructive sampling (Lewis and Harshberger 1976; Crary 1986). Fuels were harvested from as many 0.4m² or 0.16m² plots as time permitted. Usually, four to ten plots were defined with frames of 0.5 inch PVC tubing in areas that characterized the fuels of the burn unit as a whole. Plant (by species) and litter cover in the plot were estimated prior to harvesting. Material in the litter layer was harvested and separated by size classes (1-, 10-, and 100-hour time lag fuels). Shrubs and herbaceous material were harvested and separated by species and condition (live or dead). Harvested fuels were oven-dried and weighed by size class to produce fuel loading estimates in metric tonnes per hectare (mt/ha). Leaves of shrubs were weighed separately from stems. Downed woody fuel loads were also sampled using the planar intercept technique (Brown, 1974).

The weight of large scrub oak stems at Martha's Vineyard and Hollis, ME was estimated using allometric equations developed by Vescera (1996), as the time and resources required to harvest these large individuals from all plots were prohibitive. Basal diameter and status (live/dead) were recorded for stems in several 1m² plots from throughout the burn units, and weight of the *entire* plant was calculated. Because fuel models require fuel loading by size class (1-, 10-, and 100-hour time lag classes), the weight of plants with basal diameters greater than the 1hr time lag class (> 0.25") had to be divided amongst the size classes. This was done using estimates of weight distribution based upon research by W. Patterson at Myles Standish State Forest in Massachusetts (W. Patterson, personal communication). The total weight was distributed evenly between the three time-lag classes (1-, 10-, and 100-hour).

Loadings for 10- and 100-hour size class fuels obtained by planar intercept sampling were used in the construction of the custom fuel models. One-hour downed woody fuel and litter estimates came from the destructive harvesting techniques described above. The FBPS uses fuel depth and percent cover to calculate packing ratio (a ratio of the percentage of the fuel bed composed of fuel to the percentage of the fuel bed composed of air, i.e. the compactness of the fuel bed). Fire behavior is strongly influenced by packing ratio. Estimates of high shrub depth, litter depth, and shrub and litter cover, are *essential* inputs for custom fuel model construction. Brown's procedure for fuel depth measurement was altered to account for the unique fuel structure of PP-SO barrens and pine-oak forest. In addition to litter depth, measurements of low and high shrub depth were made for three, 1-ft sections along a 50-ft line. Cover estimates were derived from estimates of cover prior to sampling the harvest plots and from releve sampling, which was performed prior to burning most units.

Post-burn fuel loading was also determined by harvest sampling. All remaining fuel within 40cm x 40cm plots was carefully collected and placed in brown paper bags. The contents of the bags were oven-dried, separated by time-lag class, and weighed.

Fuel moistures of litter and live fuels were measured directly using techniques described by McGuire (1995). Larger fuels (10- and 100-hour fuels) were measured in the field with a digital moisture meter (Protometer) - an electronic device used to measure the moisture content of lumber. The fuels sampled with the moisture meter were recorded by species, size class, status (sound or rotten), and position in the fuel bed (on or above the ground). It is important to note that Dell'Orfano (1996, p.122) found that minor "variations in 10- and 100-hr fuel moisture contents did not affect the outcomes of fire behavior predictions at all."

Weather and Topography

Fire weather measurements of ambient air temperature, relative humidity, windspeed and wind direction were recorded at least hourly throughout each prescribed fire. Windspeed measurements were made with a small hand-held instrument (a TurboMeter), with values taken mid-flame height (approximately 1.5 m above the ground) within the burn units. Slope was measured with a clinometer.

The Temperature-Residence-Time Meter (TRTM) Setup

The TRTMs were installed in a systematic grid (usually 10m apart) surveyed with compass and field measuring tapes. Six to twelve TRTMs were employed in each burn unit, depending on the size of the unit and time and labor available for set-up prior to the burns. During burns we noted general burning patterns (back, head, and flank fires) and directions of spread). Careful post-fire measurements between TRTM locations allowed for triangulating distances and calculating rates of spread based on burning patterns and the known fire-arrival times at each TRTM. Fire residence time at specific locations was calculated from the TRTM record of fire arrival and departure times (Appendix D).

Prescribed Fire Execution

The prescribed fires were executed with the intention of sending a high-intensity headfire across the research portions of the burn units. We tried to create "free ranging headfire" conditions across the monitoring area, as predicted by the Rothermal model of fire spread. Safety constraints and varying weather conditions (chiefly with regard to wind speed and direction) resulted in varying degrees of success in this regard. These were controlled burns and not true wildfire conditions, and the custom models reflect this.

Results and Discussion

Data sets from five prescribed fires were chosen for this study. Each study site exhibited unique fire behavior. See Appendix B photos depicting typical fire behavior for each site. Fuel moisture and fire weather data for each burn day are found in Table 1.

Table 1: Fuel moisture (in percent) by size class, and fire weather data for individual prescribed burns.

SITE / DATE	1 hr	10 hr	100 hr	Live	Herb	Midflame Windspeed (mph)	Dry Bulb (°F)	% Relative Humidity
Martha's Vineyard 6-12-96	11	17	18	70	NA	4	76	73
Cape Cod TP01 8-4-95	14	20	21	70	NA	2	83	78
Cape Cod TP06 7-22-96	12	13	14	70	NA	3	77	45
Hollis I-A 6-23-95	8	12	13	70	142	3.5	79	40
Hollis II-E 7-12-96	12	17	18	70	142	6	84	46

Note: 7% Slope at Cape Cod plot TP06. Other sites had slope values of 0%.

Estimated rates of spread and fuel consumption estimates were used to calculate fireline intensity using Byram's equation (Table 2).

Table 2: Equation inputs and calculated fireline intensity for experimental prescribed burns.

SITE / DATE	Pre-Burn Fuel Load (kg/m²)	Post-Burn Fuel Load (kg/m²)	Fuel Consumed (kg/m²)	Measured Rate of Spread (m/min)	Byram's Fireline Intensity (kW/m/s)
Martha's Vineyard 6-12-96	2.89	.48	2.41	13.7	10,313
Cape Cod TP01 8-4-95	1.88	.55	1.33	4.24	1757
Cape Cod TP06 7-22-96	1.88	.61	1.28	6.7	2660
Hollis I-A 6-23-95	2.29	.71	1.58	3.8	1852
Hollis II-E 7-12-96	2.29	.64	1.65	5.67	2904

A narrative description of each burn follows.

Martha's Vineyard, MA (6-12-96)

Martha's Vineyard exhibited the most active fire behavior, both in terms of rate of spread and fireline intensity. Headfire flame lengths (the most difficult fire behavior parameter to accurately measure) approached 5 meters or higher (personal observation). At times, flame lengths in areas of converging lines of fire were higher than the scattered tree oaks (see photos). Jackpots of dead fuels or small open patches of heath made fire behavior variable across the burn unit as a whole. Radiant heat was very high and kept the burn crew at a distance. The closest I could get to the upwind side of fire is shown in the photos (Appendix B).

Cape Cod National Seashore, MA (8-4-95 and 7-22-96)

Fire behavior in the pine-oak forests of the Cape Cod National Seashore was quite uniform due to the uniformly thick litter layer and fairly continuous shrub cover. Dense canopy cover and the thick, mostly deciduous litter layer prevented significant herbaceous growth, thereby reducing fire intensity and rates of spread. The huckleberry proved to be very volatile, at times acting as a ladder fuel and enabling a few pitch pines to torch. Flame lengths ranged from 1 to 2 meters, often reaching higher and torching a few individual 40-foot pitch pines. Midflame windspeeds were lower at the Cape due to the wind-reducing effect of the nearly continuous tree canopy.

Hollis, ME (6-23-95 and 7-12-96)

The fires in the Hollis barrens were the most variable in behavior. Flame lengths ranged from 1 to 2 meters. The substantial green live-fuel load made for true growing-season burning conditions. Bracken fern and sedge in the herbaceous layer; flammable growing-season blueberry and scrub oaks in the shrub layer; and an open canopy of pitch pine and gray birch allowed for relatively high fireline intensities, low rates of spread, and lots of smoke.

Custom Fuel Modeling

Using the fuel loading measurements, I developed custom fuel models for each of the study sites using the NEWMDL program of BEHAVE. I generally followed the directions for constructing custom models with previously inventoried fuel data (see Burgan and Rothermal 1984). For the Martha's Vineyard and Hollis models, I averaged the low and high shrub heights to arrive at shrub depth. Because the Cape Cod site had only one shrub layer, I used an average of the maximum shrub heights. Since I was averaging many measurements of maximum shrub depth at set increments along transects at all three sites, I did not reduce these values by 70% as recommended by Burgan and Rothermal (1984). Patterson (1998) followed this line of reasoning in the construction of a fuel model for the PP-SO barrens at Myles Standish State Forest in southeastern Massachusetts.

The first custom models for Martha's Vineyard and the Cape (the sites with huckleberry present) greatly underestimated fire behavior. Dell'Orfano (1996) suggested that the Fire Behavior Prediction System does not predict fire behavior in shrub-land fuel types very well, because they have heterogeneous fuel beds. The fires in these fuel types are, in fact, crown fires (of a sort), and not free ranging surface fires. Dell'Orfano (1996) and Patterson (1998) suggested that packing ratios should be reduced (by increasing shrub height and/or percent cover) to account for the flammable nature of the shrubs and heterogeneity of the fuel bed. I found this to be true. I manipulated (raised) the fuel depth and percent cover for the Martha's Vineyard and Cape custom models. This was done by trial and error with the intention of reducing the packing ratios so the models predicted the observed fire behavior more accurately. I compared the accuracy of these models with the fire measurements using the TSTMDL and DIRECT programs of BEHAVE. The final custom fuel models for Martha's Vineyard (MV5), Cape Cod (Cape Cod 4), and Hollis (Hollis 3) are found on Figures 6 and 7. The input values for these models are found in Appendix C.

Table 3: Shrub fuel data and correction factors used in custom fuel model development

Custom Fuel Model	Measured Shrub Fuel Depth (ft.)	Measured % Shrub Cover	Required Shrub Fuel Depth (ft.)	Required % Shrub Cover	Correction Factor for Shrub Depth	Correction Factor for % Shrub Cover
Martha's Vineyard	3.4	52	4.18	80	1.23	1.54
Cape Cod	3.3	65	4	90	1.21	1.38
Hollis (dynamic)	1.79	80	1.79	80	1	1

Table 3 presents the shrub depths and percent shrub cover values required for the construction of accurate fuel models. I calculated the correction factors for adjusting the observed shrub depth and percent cover. Correction factors were calculated by dividing required values and the measured values. These correction factors can be used as a guide in the construction of other site-specific fuel models in similar fuel types.

Results are shown as bar graphs and "observed vs. predicted" forms (Figures 8-11). To demonstrate the differences between the standard NFFL model predictions and observed fire behavior, I used the DIRECT program of BEHAVE to generate fire behavior characteristics for the fuel models 4, 6, and 7. Fuel model 4 greatly over-estimates rates of spread at all sites, and over-estimates fireline intensity at the Cape Cod and Hollis sites. Fuel model 4 *under*-predicts fireline intensity at Martha's Vineyard. However, I believe there is an explanation for this. Finney and Martin (1992) note that substantial amounts of glowing phase combustion can inflate estimates of fuel consumed by the flaming front. Based on the average measured residence time and personal observations, there was substantial glowing phase/post-flaming-front combustion at Martha's Vineyard. The residence times recorded by the TRTMs at Martha's Vineyard averaged almost 6 minutes compared to about two minutes at the other study sites (Appendix D). For that reason, I believe my estimates of fuel consumption by the flaming front and, from that, fireline intensity at Martha's Vineyard are too high.

The custom dynamic model for Hollis predicts fire behavior more accurately than either fuel models 4, 6 or 7. Observed fireline intensities (Figure 10) were less than those predicted by fuel model 4 and greater than those predicted by fuel models 6 and 7. Abundant live fuels and high packing ratios at Hollis resulted in low rates of spread, even under relatively high windspeed condition (Unit II-E). In contrast to Martha's Vineyard and Cape Cod (Figure 8), the observed rates of spread were actually *less than* those predicted by fuel models 6 and 7. The dynamic modeling feature of NEWMDL was able to capture this low rate of spread/high intensity phenomena in the custom model.

By following the fuel sampling methods and custom modeling techniques described in this report, prescribed fire planners can construct more accurate fuel models for predicting fire behavior. The NEWMDL/BEHAVE method of custom fuel modeling must be manipulated for these heterogeneous fuel types during the dormant season or where there is not a significant live herbaceous fuel component (e.g. at our Truro and Martha's Vineyard sites). At these sites, shrub depths and percent cover of shrubs must be inflated to artificially reduce the packing ratio. The correction factors presented in this report serve as a guide for adjusting these values and producing more accurate custom fuel models.

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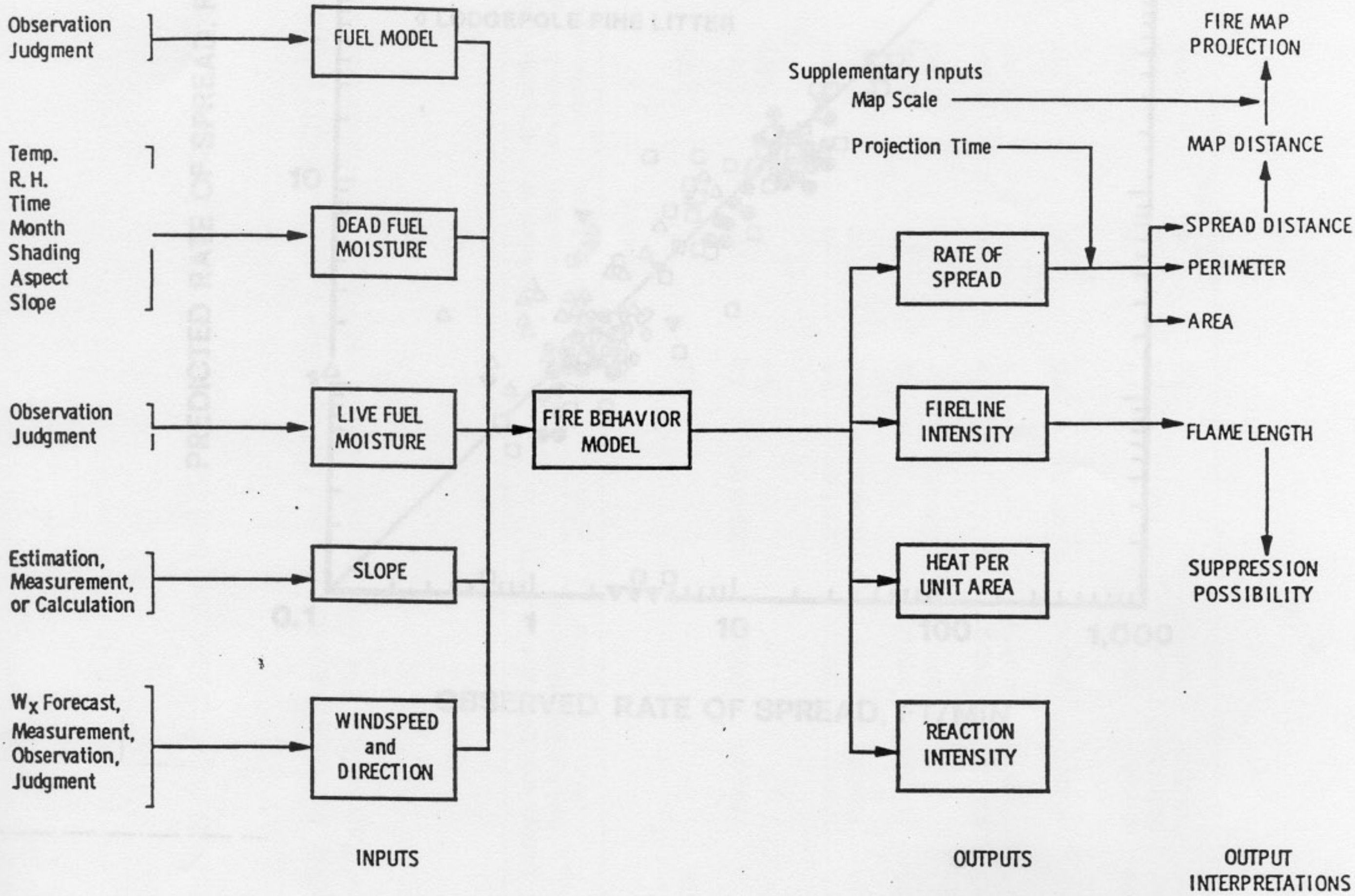


Figure 1 - Fire behavior prediction system information flow (Rothermal 1983).

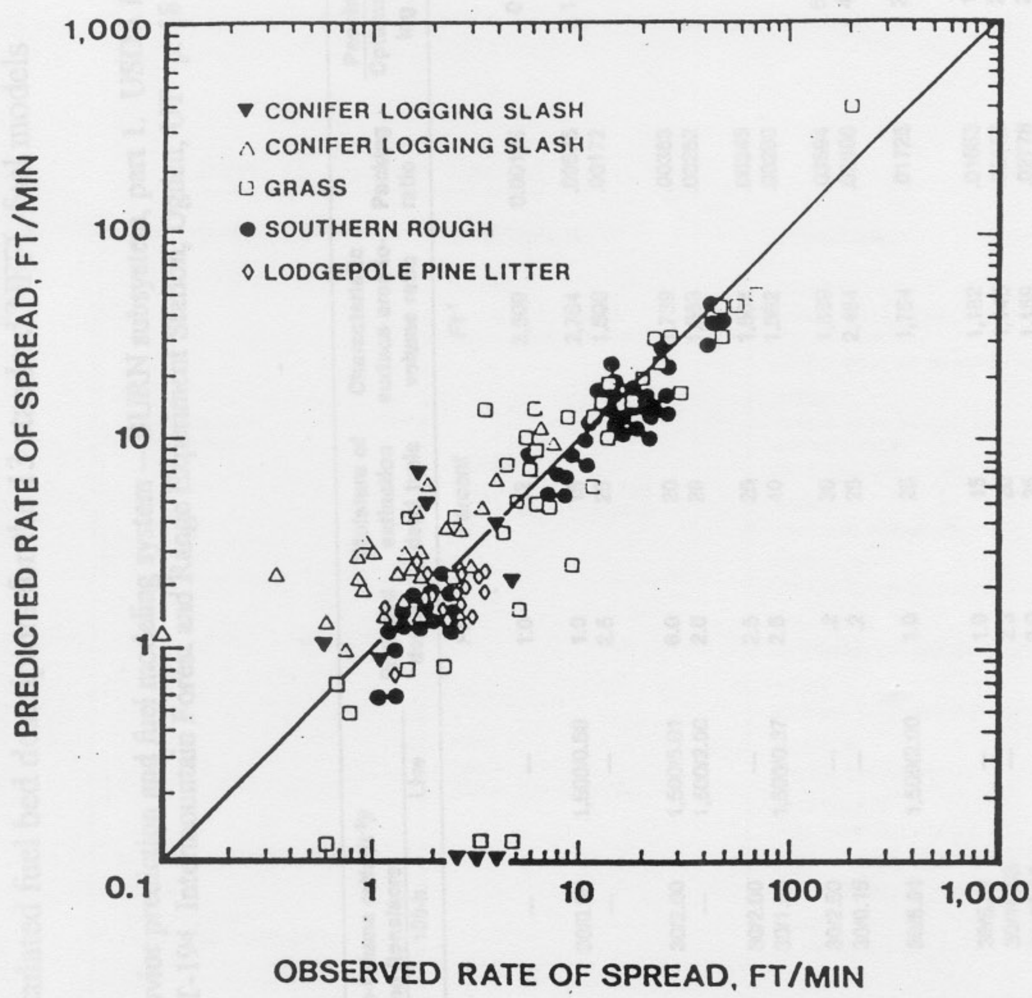


Figure 2 - Field verification of the linear trend between predicted and observed spread rates for a wide range of fuels (Rothermal 1983).

Figure 3: Fuel model parameters and calculated fuel bed descriptors for the 13 standard NFFL fuel models

From: Andrews, P.L. 1986. BEHAVE: fire behavior prediction and fuel modeling system -- BURN subsystem, part 1. USDA Forest Service General Technical Report INT-194. Intermountain Forest and Range Experiment Station, Ogden, UT. p. 18

Fuel model	Typical fuel complex	Surface-area-to-volume ratio(ft^{-1})/ fuel loading (tons/acre) 1-h	10-h	100-h	Live	Fuel bed depth	Moisture of extinction dead fuels	Characteristic surface area-to-volume ratio	Packing ratio	Packing ratio / Optimum packing ratio
						Ft	*Percent*	*Ft[1]*		
	Grass and grass-dominated									
1	Short grass (1 ft)	3,500/0.74	—	—	—	1.0	12	3,500	0.00106	0.25
2	Timber (grass and understory)	3,000/2.00	109/1.00	30/0.50	1,500/0.50	1.0	15	2,784	.00575	1.14
3	Tall grass (2.5 ft)	1,500/3.01	—	—	—	2.5	25	1,500	.00172	.21
	Chaparral and shrub fields									
4	Chaparral (6 ft)	2,000/5.01	109/4.01	30/2.00	1,500/5.01	6.0	20	1,739	.00383	.52
5	Brush (2 ft)	2,000/1.00	109/0.50	—	1,500/2.00	2.0	20	1,683	.00252	.33
6	Dormant brush, hardwood slash	1,750/1.50	109/2.50	30/2.00	—	2.5	25	1,564	.00345	.43
7	Southern rough	1,750/1.13	109/1.87	30/1.50	1,500/0.37	2.5	40	1,562	.00280	.34
	Timber litter									
8	Closed timber litter	2,000/1.50	109/1.00	30/2.50	—	.2	30	1,889	.03594	5.17
9	Hardwood litter	2,500/2.92	109/0.41	30/0.15	—	.2	25	2,484	.02500	4.50
10	Timber (litter and understory)	2,000/3.01	109/2.00	30/5.01	1,500/2.00	1.0	25	1,764	.01725	2.35
	Slash									
11	Light logging slash	1,500/1.50	109/4.51	30/5.51	—	1.0	15	1,182	.01653	1.62
12	Medium logging slash	1,500/4.01	109/14.03	30/16.53	—	2.3	20	1,145	.02156	2.06
13	Heavy logging slash	1,500/7.01	109/23.04	30/28.05	—	3.0	25	1,159	.02778	2.68

[1]Heat content = 8,000 Btu/lb for all fuel models.

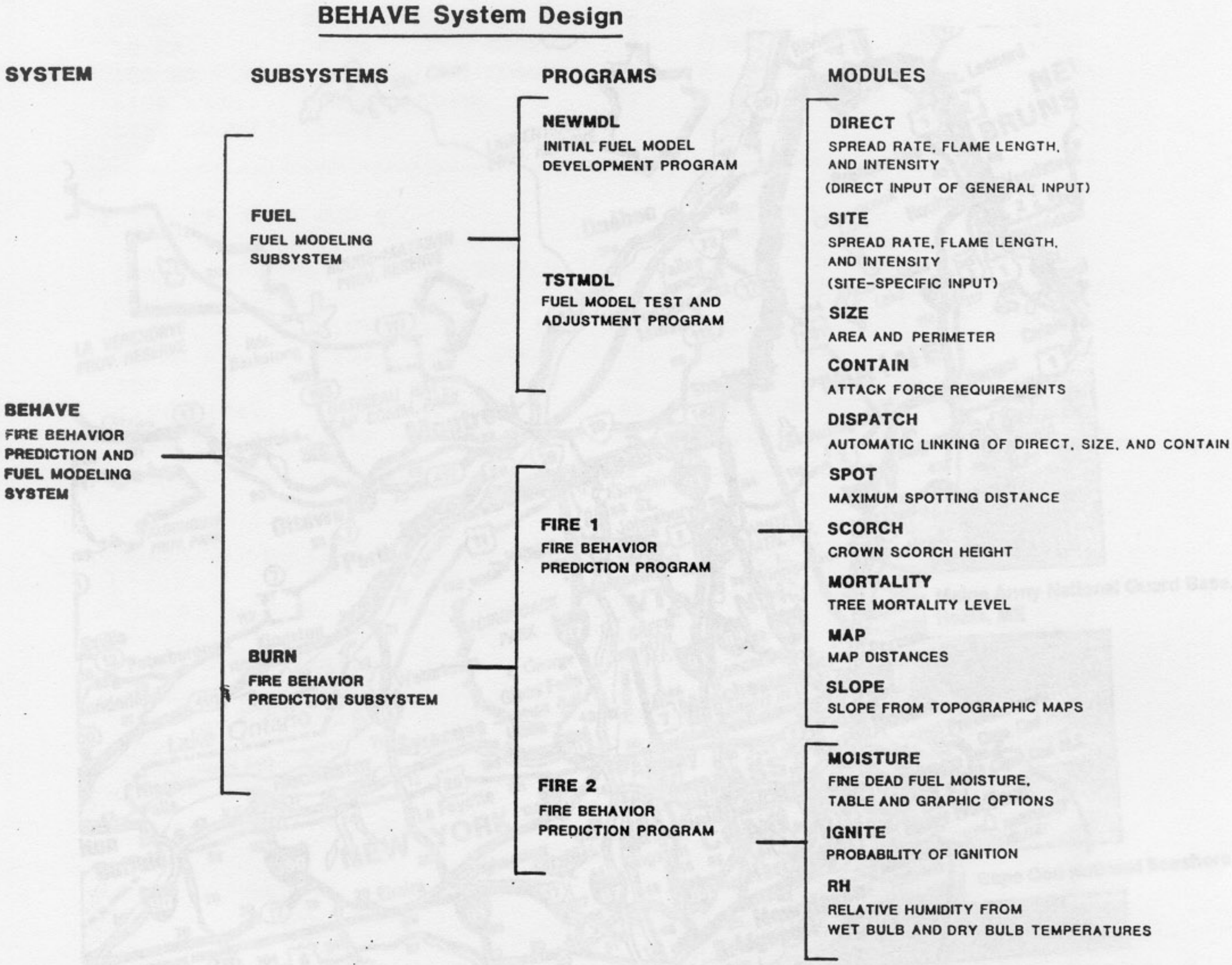


Figure 4 - Subsystems, programs, and modules of the BEHAVE system (Andrews and Chase 1989)

Figure 5: Map of the Northeast showing locations of study sites

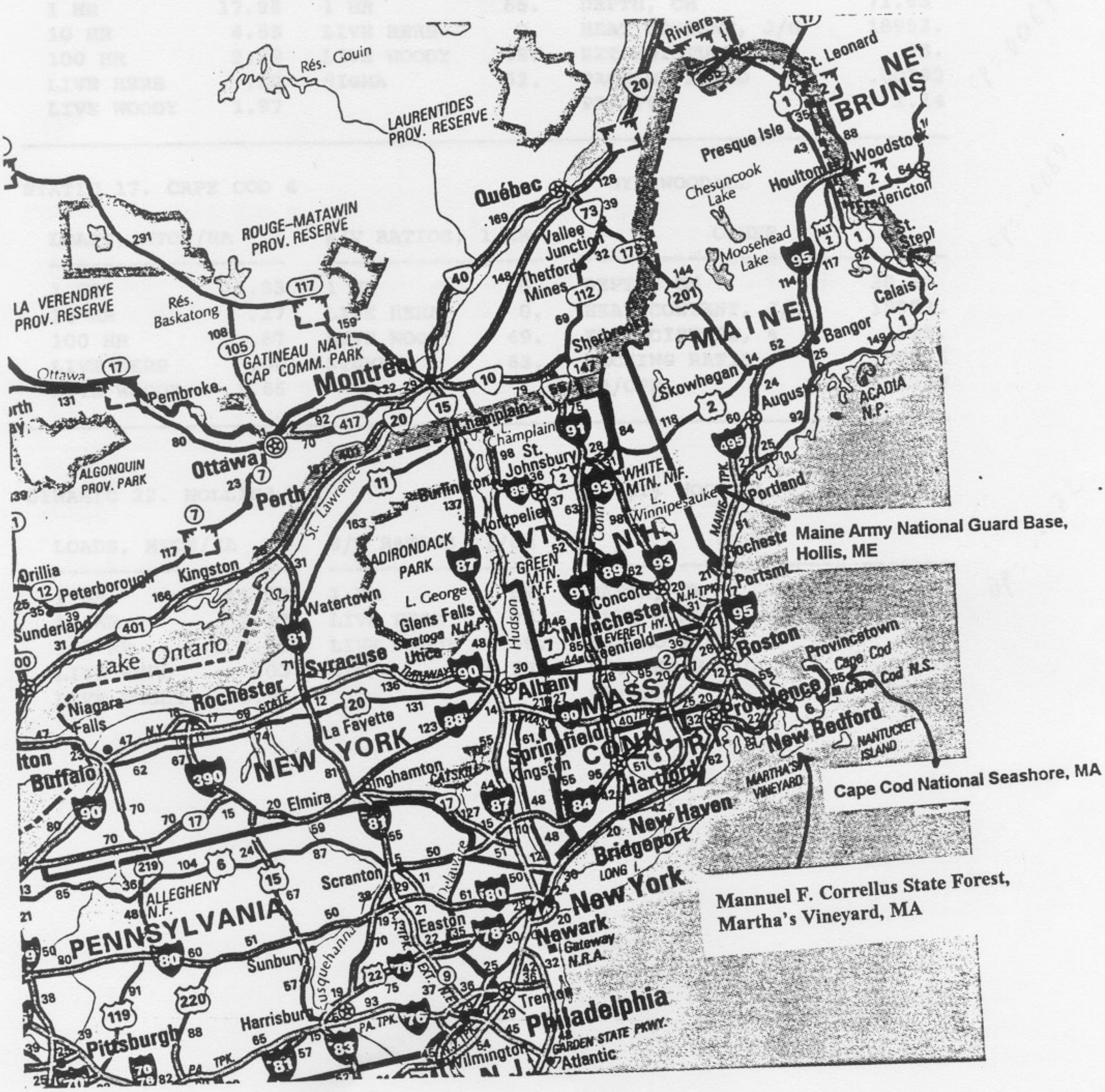


Figure 6: Custom fuel models for each study site (metric units)

STATIC 29. MV5 — BY: WOODALL

LOADS, MTON/HA		S/V RATIOS, 1/CM		OTHER	
1 HR	17.95	1 HR	66.	DEPTH, CM	71.93
10 HR	4.53	LIVE HERB	0.	HEAT CONTENT, J/G	18953.
100 HR	2.29	LIVE WOODY	49.	EXT MOISTURE, %	23.
LIVE HERB	.00	SIGMA	62.	PACKING RATIO	.00792
LIVE WOODY	1.97			PR/OPR	1.14

STATIC 17. CAPE COD 4 — BY: WOODALL

LOADS, MTON/HA		S/V RATIOS, 1/CM		OTHER	
1 HR	13.83	1 HR	66.	DEPTH, CM	38.10
10 HR	.27	LIVE HERB	0.	HEAT CONTENT, J/G	18983.
100 HR	.67	LIVE WOODY	49.	EXT MOISTURE, %	25.
LIVE HERB	.00	SIGMA	63.	PACKING RATIO	.00946
LIVE WOODY	1.65			PR/OPR	1.38

DYNAMIC 22. HOLLIS3 — BY: WOODALL

LOADS, MTON/HA		S/V RATIOS, 1/CM		OTHER	
1 HR	11.09	1 HR	66.	DEPTH, CM	29.26
10 HR	2.47	LIVE HERB	74.	HEAT CONTENT, J/G	19399.
100 HR	1.59	LIVE WOODY	49.	EXT MOISTURE, %	28.
LIVE HERB	.03	SIGMA	59.	PACKING RATIO	.01539
LIVE WOODY	3.51			PR/OPR	2.14

Figure 7: Custom fuel models for each study site (English units)

STATIC 29. MV5 BY: WOODALL

LOADS, T/AC		S/V RATIOS, 1/FT		OTHER	
1 HR	8.01	1 HR	2000.	DEPTH, FT	2.36
10 HR	2.02	LIVE HERB	0.	HEAT CONTENT, BTU/LB	8154.
100 HR	1.02	LIVE WOODY	1500.	EXT MOISTURE, %	23.
LIVE HERB	.00	SIGMA	1898.	PACKING RATIO	.00792
LIVE WOODY	1.97			PR/OPR	1.14

STATIC 17. CAPE COD 4 BY: WOODALL

LOADS, T/AC		S/V RATIOS, 1/FT		OTHER	
1 HR	6.17	1 HR	2000.	DEPTH, FT	1.25
10 HR	.12	LIVE HERB	0.	HEAT CONTENT, BTU/LB	8167.
100 HR	.30	LIVE WOODY	1500.	EXT MOISTURE, %	25.
LIVE HERB	.00	SIGMA	1914.	PACKING RATIO	.00946
LIVE WOODY	1.65			PR/OPR	1.38

DYNAMIC 22. HOLLIS3 BY: WOODALL

LOADS, T/AC		S/V RATIOS, 1/FT		OTHER	
1 HR	4.95	1 HR	2001.	DEPTH, FT	.96
10 HR	1.10	LIVE HERB	2250.	HEAT CONTENT, BTU/LB	8346.
100 HR	.71	LIVE WOODY	1500.	EXT MOISTURE, %	28.
LIVE HERB	.03	SIGMA	1813.	PACKING RATIO	.01539
LIVE WOODY	3.51			PR/OPR	2.14

Figure 8: Observed rates of spread for each prescribed fire compared to predicted values using site-specific custom models and NFFL fuel models 4, 6 and 7.

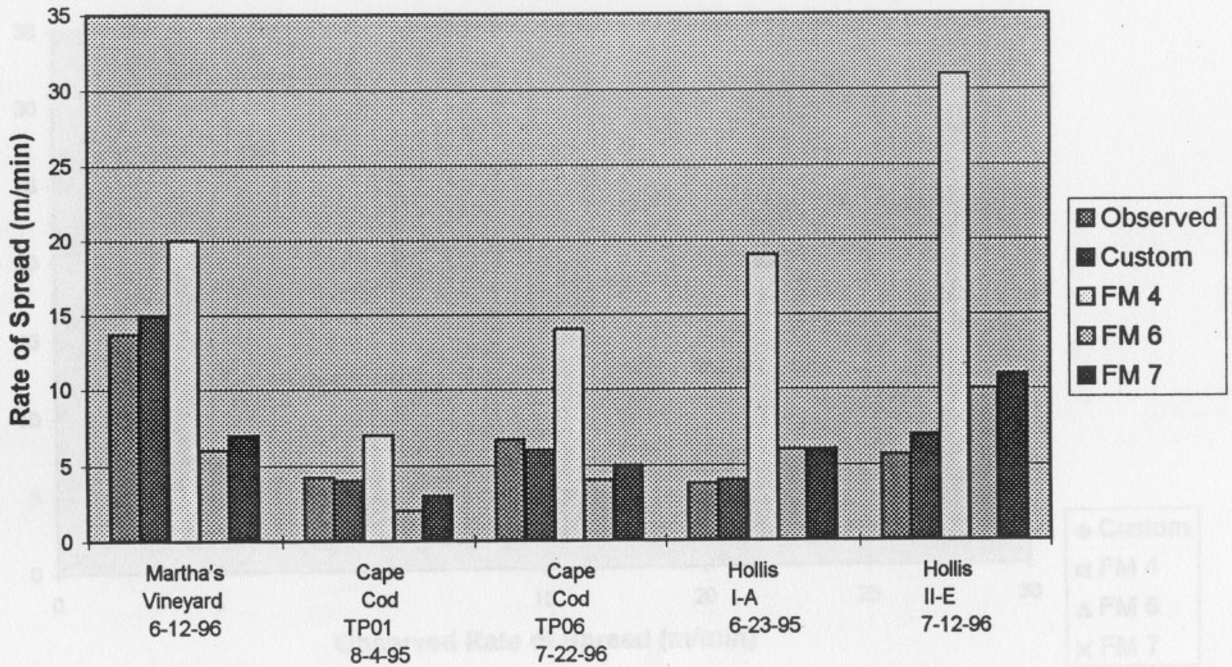


Figure 9: Rate of spread - observed vs. predicted values using site-specific custom models and NFFL fuel models 4, 6 and 7.

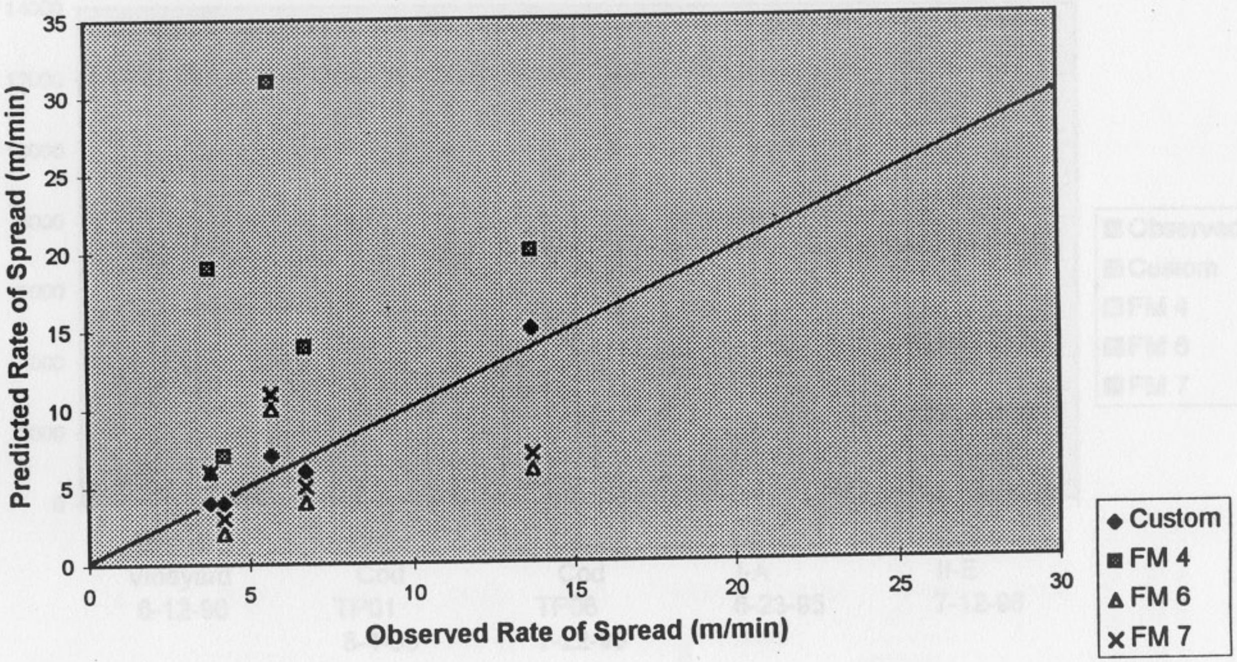


Figure 10: Observed fireline intensities for each prescribed fire compared to predicted values using site-specific custom models and NFFL fuel models 4, 6 and 7.

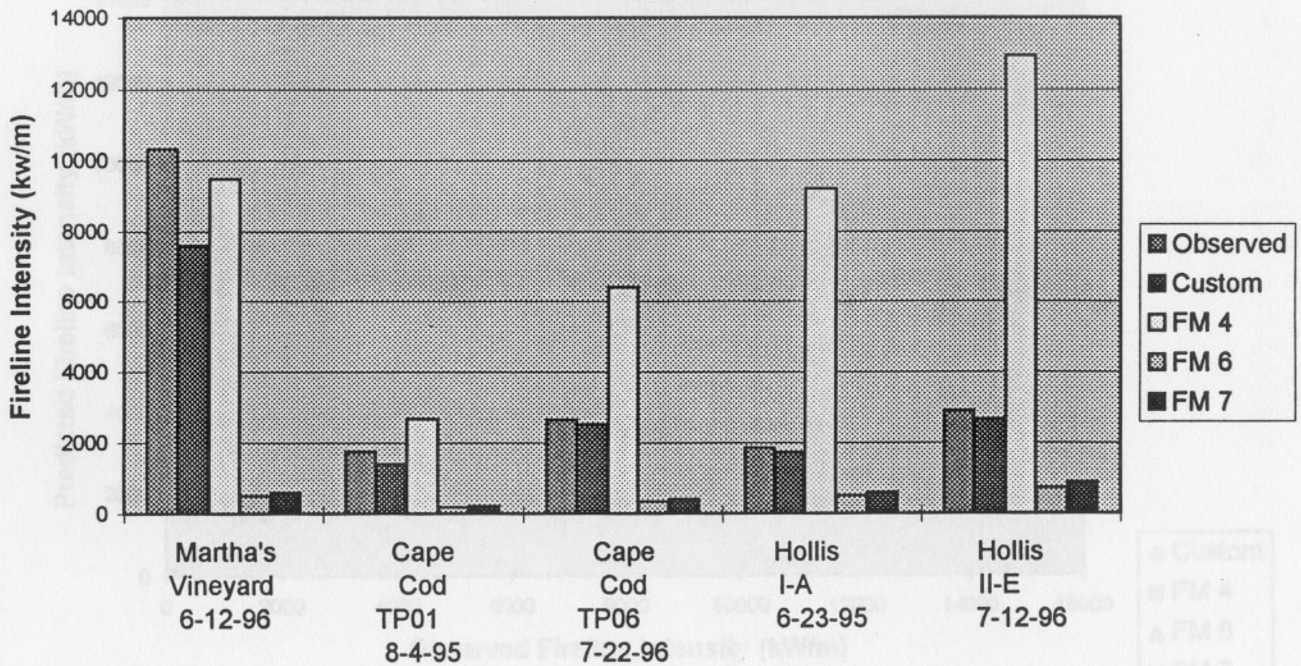
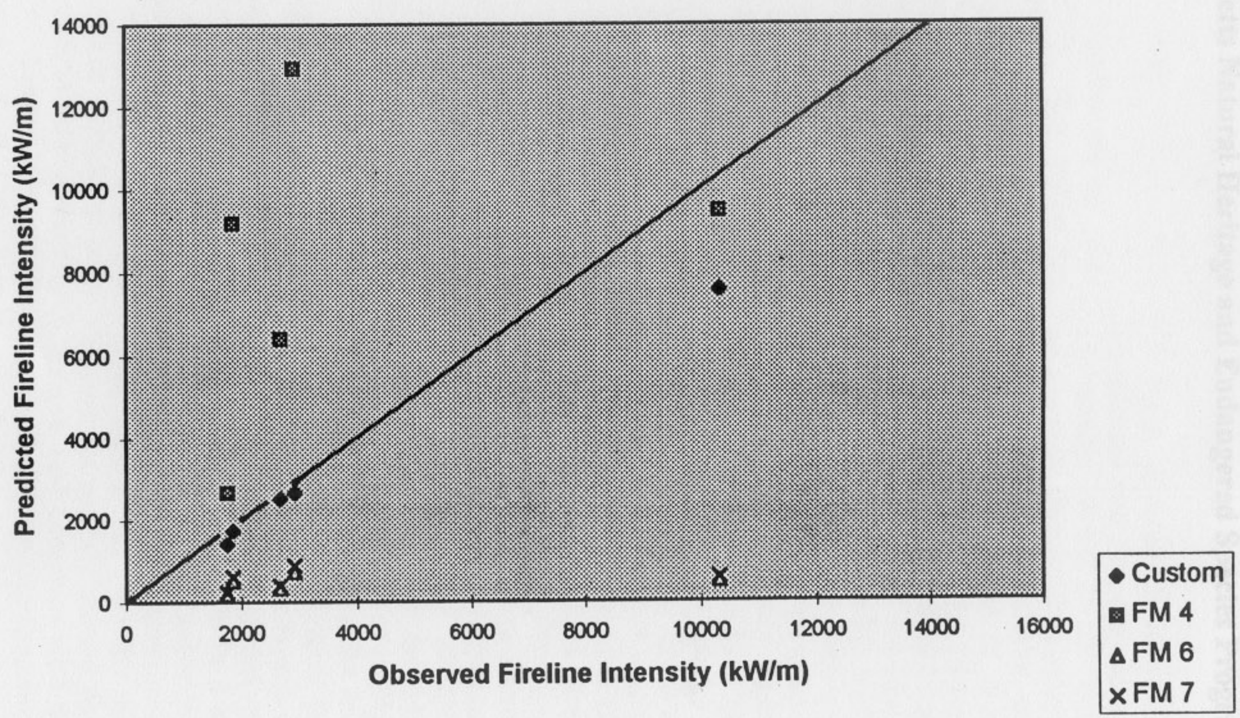


Figure 11: Fireline intensity - observed vs. predicted values using site-specific custom models and NFFL fuel models 4, 6 and 7.



APPENDIX A

Natural Community Fact Sheet
Pitch Pine/Scrub oak Barrens

Massachusetts Natural Heritage and Endangered Species Program

Natural Heritage & Endangered Species Program

Commonwealth of Massachusetts
Division of Fisheries & Wildlife
Route 135
Westborough, MA 01581
(508) 792-7270 ext. 200

Natural Community Fact Sheet
Pitch pine/Scrub oak Barrens

Description

Pitch pine/scrub oak barrens are an open shrubland plant community, that occurs on outwash sandplains. Pitch pine/scrub oak barrens, also called oak/pine scrub or pine barrens, typically have an open canopy of pitch pine and a nearly impenetrable understory of scrub oaks up to 2-3 meters (7-10 feet) tall and shorter huckleberry about a meter (3 feet) tall.. There is often a mosaic of scrub oak which may be thick enough to exclude other plants, openings with lowbush blueberry, bearberry, or lichen, and grassland or heathland in low areas. White pine may also occur in less dry sites. Areas with tree oaks or abundant pine trees of either species are considered to be woodland or forest, not barrens.

Environment

Pitch pine/scrub oak barrens occur on deep, coarse, well-drained sands derived from glacial outwash, in the coastal plain, the Connecticut River Valley, and other scattered areas throughout the northeast. The sands are acidic, nutrient poor and drought prone. The low vegetation and sandy soils contribute to a tendency to be hotter than more mesic sites on summer days, with greater cooling at night, so have great temperature variations daily. The dry environment with low humidity contributes to the loss of heat at night, as in a desert. Exposure to the temperature variations may make plants more susceptible to other damaging factors such as insects or disease. In pitted outwash plains or rolling moraines, some low bowls, or kettles, are frost pockets and have more heath and lichen and less oak and pine. Deeper kettles may intersect the water table and have a Coastal Plain Pond at the bottom.

Pitch pine/scrub oak barrens are a fire maintained and fire dependent type of natural community: some of the component species depend on recurrent fires for their existence, and many of the species have volatile oils that actually encourage the spread of fires once they are ignited. Species of the community tend to be adapted to occasional light fires: scrub oaks and huckleberries sprout readily from their root crowns and pitch pine has thick bark that resists fire damage. Pitch pine can grow new branches from the stem, and it produces some cones that release their seeds only when heated by fire. Such species can sprout back vigorously once the fire has passed; other species of invading trees don't survive the fire. Some of the herbaceous species have long lived seeds that stay in the duff for years and germinate after fire; the plant becomes abundant for the first few years after a fire before the larger plants grow sufficiently to shade them out. Fire increases the rate of nutrient cycling: organic material that is slow to rot in the site's dry conditions releases its nutrients in a pulse in the ash after a fire. The pulse of nutrient availability results in lush growth of the plants in the first few years, with increased variety of insects that eat the plants, and birds that eat the insects and berries of the plants. Prescribed burns that remove accumulated dead needles and leaves on a regular basis can be used to reduce the danger from wildfires, and help maintain the natural community. Studies have shown that diversity of native species is greatest in recently burned pitch pine/scrub oak barrens, and decreases with time after a fire, as scrub oak increases its dominance.

Pitch pine/scrub oak barrens can be a successional stage: if there is no disturbance such as fire, tree oaks and white pine can invade and take over. Other sites may receive seeds of the forest species, but recurrent disturbances limit their germination and growth. Open communities are part of a structural and successional continuum between oak-pine woodlands with closed canopies of tree species and the structurally simpler open heathlands with no trees and many low shrubs. Some of the areas now covered by pitch pine/scrub oak may have been culturally produced: the deforestation of Massachusetts during and after the 1600s may have resulted in removal of sufficient nutrients and loss of topsoil that the forests from which masts of white pine were cut can no longer be supported. Grazing and over-cultivation may also have contributed to producing scrub oak/pitch pine areas. However, given the prevailing soil conditions, the community type must have always been widespread. A natural fire regime of occasional large wildfires would have contributed its maintenance in the areas with few natural fire breaks. Native Americans burned the woods to improve berry crops and hunting, and must have contibuted to the size of the barrens.

Many of the plant species found in pitch pine/scrub oak barrens grow on rock outcrops and ridges north and west of the coastal plain, such as the Blue Hills and Middlesex Fells near Boston, Cape Ann, the ridge top openings of the Holyoke Range in the Connecticut River Valley, and Mt. Everett and Monument Mountain in the southern Berkshires. These are also dry, nutrient poor, acidic, harsh environments.

Characteristic species of Pitch pine/Scrub oak Barrens in Massachusetts

Pitch pine/scrub oak barrens are not floristically very diverse; the combination of species plus the physical structure of the vegetation defines the natural community. The main tree species is pitch pine (*Pinus rigida*) with the shrubs scrub oak (*Quercus ilicifolia*) dominant near the coast and dwarf chinquapin oak (*Q. prinoides*) more common inland. Huckleberry (*Gaylussacia baccata*) is shorter than the oaks and often grows in dense clones. Lowbush blueberries (*Vaccinium angustifolium* and *V. pallidum*) may form large patches, or grow mixed with other species. In the openings between the shrubs, there are usually clones of bearberry (*Arctostaphylos uva-ursi*), large patches of fruticose lichens and intermixed areas with sedges (primarily *Carex pensylvanica and C. rugosperma.*) or little blue stem (*Schizachyrium scoparium*). In Massachusetts large patches of lupine (*Lupinus perennis*), important for butterflies, are now unusual. A number of other species regularly occur in low numbers including cow wheat (*Melampyrum lineare*) and mayflower (*Epigaea repens*). The particular plants that occur may provide information on the site: wintergreen (*Gaultheria procumbens*) and bracken fern (*Pteridium aquilinum*) tend to occur in less dry woodlands and golden heather (*Hudsonia ericoides*) is most common in open, dry edges. The inland variant of scrub oak/ pitch pine barrens have successional areas with trembling aspen (*Populus tremuloides*), gray birch (*Betula populifolia*), and black cherry (*Prunus serotina*). Hairy Wild Lettuce (*Lactuca hirsuta* var. *sanguinea*), Lion's Foot (*Prenanthes serpentaria*), Broom crowberry (*Corema conradii*), and aromatic boneset (*Eupatorium aromaticum*) are rare plants whose primary habitat is pine barrens.

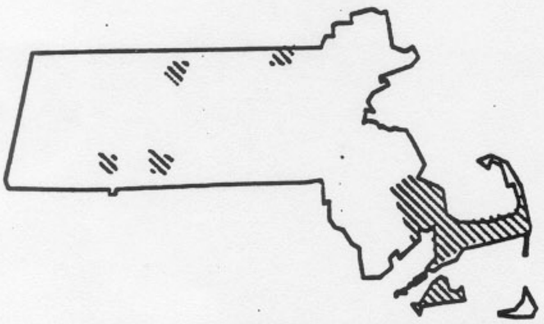
The bird fauna is generally that of oak woodlands: Rufous-sided Towhee (*Pipilo erythrophthalmus*) pine warbler (*Dendroica pinus*), prairie warbler (*Dendroica discolor*), and ruffed grouse (*Bonasa umbellus*) are common. Whip-poor-will (*Caprimulgus vociferus*) and Common Nighthawk (*Chordeiles minor*) now have larger populations in sandy openings of pine barrens than other parts of their increasingly restricted natural distributions. American Woodcock (*Philohela minor*) also use the openings. Heath hens (*Tympanuchus cupido cupido*), a now extinct subspecies of prairie chicken, were adapted to pitch pine/scrub oak communities: they ate scrub oak acorns and berries in the openings, and used scrub oak for cover. Exclusion of fire followed by very large, hot fires in their habitat is considered to be a contributory cause to their extinction.

Mammalian fauna of pine barrens is depauperate: no species depend on the habitat for their existence. A variety of small mice and voles use the scrub oak for cover and feed where they find acorns or berries. Larger mammals seem to prefer woodlands where they can move more easily.

Pitch pine/scrub oak barrens have a rich lepidopteran fauna. The barrens buckmoth (*Hemileuca maia*), a rare moth dependent on scrub oak is threatened throughout its northern range. Several other rare species of moths and butterflies have a particular affinity for pine barrens as well. Some of these moths are thought to no longer exist in pine barrens that have been reduced in size to less than a thousand acres. The Karner Blue butterfly (*Lycæides melissa samuelis*) which is dependent on large numbers of lupine (its larval food plant) and large acreage of habitat has not been found in Massachusetts for many years: its population has recently declined precipitously in New Hampshire and its former strongholds in the midwest.

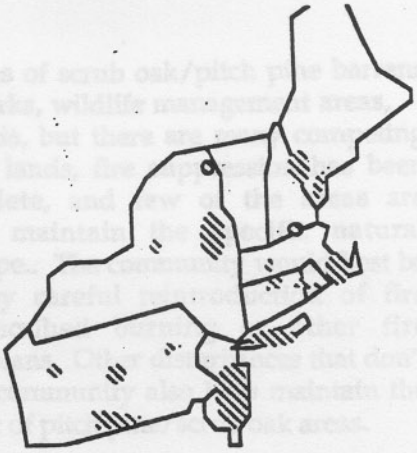
Range

There are many acres of this natural community in southeastern Massachusetts and remnants in the Connecticut River Valley. Pitch pine did not occur on Nantucket until planted by European settlers, but scrub oak and heath species are abundant there. Martha's Vineyard has many acres of the pitch pine/ scrub oak community. The type of natural community occurs throughout northeastern North America. In New England there are several variants of the community-type: the boreal variant occurs in Maine and New Hampshire, the inland variant occurs in upstate New York, central Massachusetts and central Connecticut, and southeastern Massachusetts and Rhode Island have a coastal variant.



Range of Pitch pine/Scrub oak Barrens in Massachusetts

The pitch pine/scrub oak barrens of Long Island represent a variation of the coastal type. The Pinelands of New Jersey and the pine barrens of the Poconos in Pennsylvania share some of the same structural conditions and species, but are sufficiently different to be considered other community-types.



Distribution of Pitch pine/Scrub oak Barrens

Status in Massachusetts

The community-type is severely threatened by exclusion of fire and by human development. Despite the aerial extent of the community type, the flatness of much of the terrain makes it very developable, and the sterile sand substrate with rapid drainage has led to its being regarded as waste land. (The soils are classified as having "excessive drainage", a term denoting difficulty in raising agricultural crops, although the native pine barrens species manage quite well.) Many scrub oak/pitch pine barrens occur on large aquifers, and development may threaten the quality of the water. In recent years, distribution of the community has been reduced with the spread of development: southeastern Massachusetts, Cape Cod, and the Westfield/Chicopee/Springfield areas have all lost many acres of pine barrens. Connecticut's last 80 acres of pitch pine/scrub oak barrens were subdivided within the last several years.

There are several species of butterflies and moths that depend on scrub oak/pitch pine habitats, and some of these lepidoptera require a thousand or more acres of scrub oak barrens to have enough larval food plants or successional stages to support their populations. The fragmentation of scrub oak/pitch pine barrens has been implicated in the extirpation of the Karner Blue butterfly (*Lycæides melissa samuelis*) from

Massachusetts. Small populations of both plants and animals have reduced genetic variability, and thus reduced ability to respond to changes in the environment. Populations that are already stressed may not recover from losing a generation of adults, such as occurs after spraying for Gypsy moths or mosquitoes which reduce populations of all species of adult butterflies and moths. Although plant species tend to be better able to recover from disturbances than animal species (plant seeds may stay dormant in the soil for years and other plants can occur vegetatively in remnants), fragmentation will ultimately also reduce viability of small populations of plants.

Many acres of scrub oak/pitch pine barrens are in state parks, wildlife management areas, and town lands, but there are many competing uses of these lands, fire suppression has been almost complete, and few of the areas are managed to maintain the specific natural community type.. The community would best be maintained by careful reintroduction of fire through prescribed burning or other fire management plans. Other disturbances that don't fragment the community also help maintain the natural mosaic of pitch pine/scrub oak areas.

Appendix B

Photos from research prescribed fires

Martha's Vineyard, MA: post-burn fuel loading

Martha's Vineyard, MA: pre-burn fuel loading

Martha's Vineyard, MA: headfire

Martha's Vineyard, MA: headfire converging with flanking fire


Cape Cod National Seashore, MA: pre-burn fuel loading


Cape Cod National Seashore, MA: post-burn fuel loading

Cape Cod National Seashore, MA: headfire

Cape Cod National Seashore, MA: headfire

Hollis, ME: headfire ignition

Hollis, ME: headfire

Hollis, ME: post-burn fuel loading

APPENDIX C
NEWMDL Inputs for Custom Fuel Models

Martha's Vineyard Custom Fuel Model (Static) - NEWMDL Inputs:

LITTER FUEL LOAD DATA:	1 hour	6.58 t/ac
	10 hour	0.87
	100 hour	1.076
	Depth	1.86 ft.
	% Coverage	95

SHRUB FUEL LOAD DATA:	1 hour	2.2 t/ac
	10 hour	1.49
	100 hour	0
	Leaves and Twigs	2.465
	Depth	4.18 ft.
	% Coverage	80

SURFACE TO VOLUME RATIOS:	1 hour Litter	2000 ft^2/ft^3
	1 hour Shrub	2000
	Live Woody	1500

HEAT CONTENT: = 8000 Btu/lb for dead fuels
= 9000 Btu/lb for live twigs and leaves

Cape Cod Custom Fuel Model (Static) - NEWMDL Inputs:

LITTER FUEL LOAD DATA:	1 hour	5.74 t/ac
	10 hour	0.12
	100 hour	0.3
	Depth	0.46 ft.
	% Coverage	100

SHRUB FUEL LOAD DATA:	1 hour	0.48 t/ac
	10 hour	0
	100 hour	0
	Leaves and Twigs	1.83
	Depth	4 ft.
	% Coverage	90

SURFACE TO VOLUME RATIOS:	1 hour Litter	2000 ft²/ft³
	1 hour Shrub	2000
	Live Woody	1500

HEAT CONTENT: = 8000 Btu/lb for dead fuels
= 9000 Btu/lb for live twigs and leaves

Hollis Custom Fuel Model (Dynamic) - NEWMDL Inputs:

LITTER FUEL LOAD DATA:	1 hour	4.97 t/ac
	10 hour	0.485
	100 hour	0.215
	Depth	0.48 ft.
	% Coverage	91
GRASS FUEL LOAD DATA:	Grass load	.31 t/ac
	Depth	0.4
	Max % live	75
	% Coverage	14
SHRUB FUEL LOAD DATA:	1 hour	0.878 t/ac
	10 hour	0.828
	100 hour	.643
	Leaves and Twigs	4.39
	Depth	1.79 ft.
	% Coverage	80
SURFACE TO VOLUME RATIOS:	Dead Grass	2500 ft^2/ft^3
	1 hour Litter	2000
	1 hour Shrub	2000
	Live Herb	2250
	Live Woody	1500

HEAT CONTENT: = 8000 Btu/lb for dead fuels
= 9000 Btu/lb for live twigs and leaves

APPENDIX D

Residence times from research prescribed fires

FIRE	RESIDENCE TIMES (minutes:seconds)	AVERAGE (minutes:seconds)
Martha's Vineyard 6-12-96	5:49, 2:20, 3:59, 7:57 7:02, 6:04, 5:37, 5:47 5:53	5:36
Cape Cod TP01 8-4-95	2:00, 1:23, 1:33, 1:25 1:37, 2:09, 2:15, 1:35 2:57, 3:03	2:00
Cape Cod TP06 7-22-96	1:50, 2:03, 1:49, 1:53 2:22, 2:22, 2:38, 5:05	2:30
Hollis I-A 6-23-95	0:41, 1:04, 0:31, 5:19 4:20	2:23
Hollis II-E 7-12-96	1:09, 2:01, 1.25, 1.11 1.36, 2.30, 2.03, 1.12 2.54	1:47