Developing Fire Behavior Fuel Models for the Wildland–Urban Interface in Anchorage, Alaska

Daniel Cheyette, T. Scott Rupp, and Sue Rodman

ABSTRACT

Fire behavior modeling systems are playing an increasingly important role in identifying areas of the wildland–urban interface (WUI) that could support intense and fast-moving wildfires. The modeling systems also can be used to prioritize areas for fuels reduction treatments. We used forest inventory data to create custom fire behavior fuel models for the Anchorage, Alaska, WUI—an area strongly impacted by a recent spruce bark beetle (*Dendroctonus rufipennis*) infestation. Eight custom fuel models were developed including a custom fuel model for a spruce bark beetle impacted forest type. NEXUS simulations indicate that the custom fuel models better describe forest structure and predict fire behavior than do parameterized standard fuel models previously used by local fire managers. Rate of spread and fireline ranged from 1–321 chains/hour and 1–2,549 Btu/ft per second, respectively, for the custom fuel models compared with 1–70 chains/hour and 1–7,929 Btu/ft per second, respectively, for the parameterized standard fuel models. Our study shows that it is both possible and feasible to create custom fuel models directly from fuels inventory data. This achievement has broad implications for land managers, particularly managers of the boreal forest, a region that is susceptible to wildfires but also home to a growing human population and increasing amounts of development.

Keywords: boreal forest, fire behavior fuel model, NEXUS, wildland fuel, wildland–urban interface

Much of the western United States and Canada is susceptible to wildfires. The potential for these fires to damage life and property is increasing because a century of fire suppression has caused wildland fuel loads to grow (Arno and Brown 1991) and the expansion of wildland–urban interface (WUI) communities is putting more people and property in harm's way (Winter et al. 2002). Forest managers are attempting to minimize the potential for wildfire damage by conducting fuel reduction treatments. Their goal is to reduce fuel loads but maintain desirable qualities of forest structure and composition (Winter et al. 2002).

Fire behavior modeling systems can be used to identify areas of the WUI that could support damaging wildfires and to prioritize fuel treatments. BehavePlus, NEXUS, and FARSITE (Systems for Environmental Management, Missoula, MT) are three such models commonly used in the United States. These models differ in terms of their capabilities, uses, and outputs but rely on the same basic fire spread algorithms: surface and crown fire algorithms developed by Rothermel (1972, 1991) and a crown fire initiation algorithm developed by Van Wagner (1977). An inherent problem with the modeling systems is that users can not directly input fuel inventory information because the algorithms homogenize key fuelbed components, namely, the loads of fine woody fuels, litter, grasses, and shrubs. Consequently, a fire behavior fuel model has to be used.

Rothermel (1972) parameterized eleven fuel models for use in his fire spread model (Scott and Burgan 2005). Albini (1976) further parameterized Rothermel's eleven models and added two additional models (Scott and Burgan 2005). These models are collectively known (and are referred to in this article) as the thirteen "standard fuel models." Anderson (1982) compiled descriptions and photographic illustrations for the standard fuel models in a guide for fire managers. Alaska fire managers have attempted to parameterize the standard fuel models to Alaska forest types (Norum 1982, Mallot 1984). These studies indicate that the standard fuel models are not well-suited to describing the fuel complexes in Alaska forests.

Scott and Burgan (2005) recently parameterized an additional forty fuel models. These models were developed from fuel types described by a variety of researchers, including several Alaska specific fuel types described by Ottmar and Vihnanek (1998, 2002) and Scott and Burgan (2005). Accordingly, several of the Scott and Burgan (2005) fuel models developed may be applicable to forest types in the Anchorage WUI.

The Fuel Characteristic Classification System (FCCS) is a newer fire behavior modeling system. The FCCS is a significant improvement over the other modeling systems because it considers individual fuelbed components—fine wood debris, litter, grasses, and shrubs—and calculates the predicted surface fire behavior based on these inputs (US Forest Service 2006). We did not consider the FCCS because it largely postdates our work and has not been tested in south central Alaska.

Finally, Canadian and interior Alaska fire managers use the Canadian Forest Fire Danger Rating System (CFFDRS) for fire behavior modeling. Unlike the BehavePlus, NEXUS, and FARSITE modeling systems, the CFFDRS is derived from empirical data and fire observations and focuses on the contribution of forest floor layer to the fuel complex (Van Nest and Alexander 1999). We did not use

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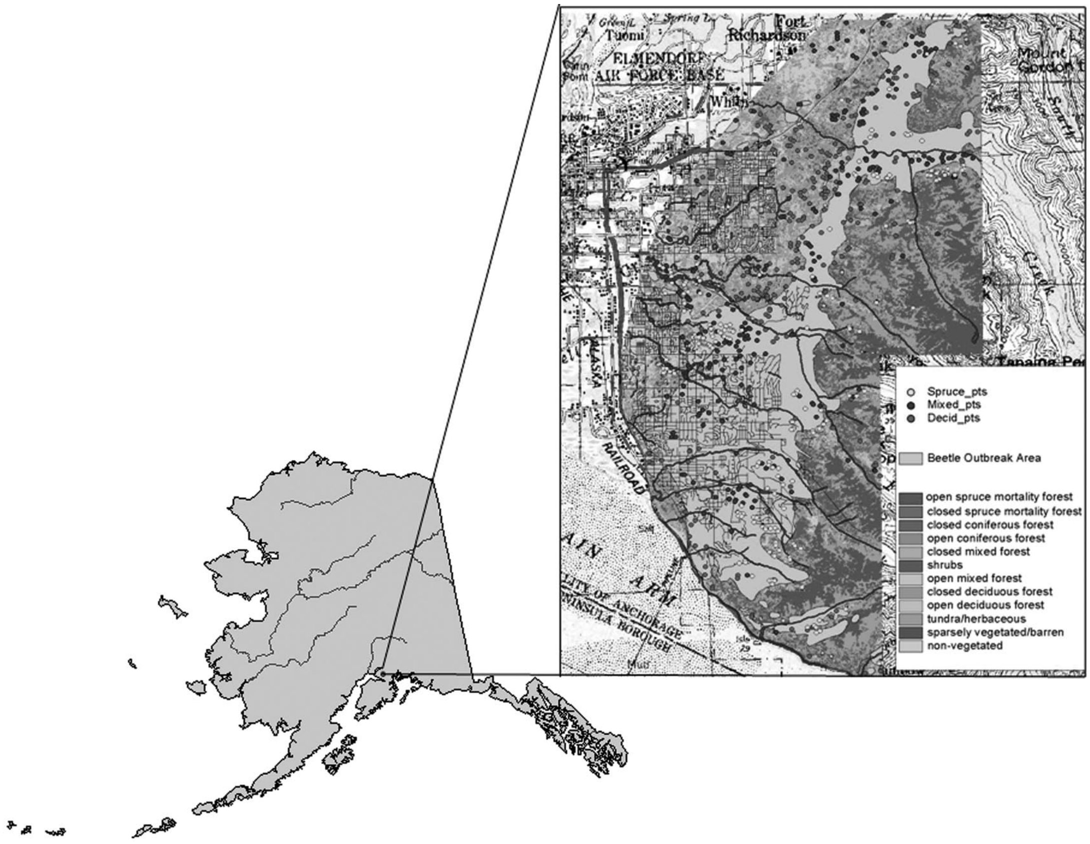

Figure 1. Anchorage, Alaska. Map locates Anchorage within the state of Alaska.

the CFFDRS because that system is not widely used in south central Alaska.

The goal of our research was to inventory the fuel complexes in the Anchorage WUI and create custom fire behavior fuel models using the inventory data. We verified the appropriateness of our custom fuel models by comparing NEXUS (Scott and Reinhardt 1999) simulation results for these models with results for fuel models previously created by Anchorage fire managers. We used NEXUS because it couples the three fire behavior algorithms in a single, integrated model that is easy to use and quickly tabulates results for several key output variables.

Methods

Study Site

Anchorage is located in south central Alaska centered at 61°10′N latitude and 150°01′W longitude (Figure 1). The Anchorage WUI is coincidental with the Anchorage Bowl, a 126 mi^2 peninsula of land that is wedged between the western slopes of the Chugach Mountains and Cook Inlet. Although Anchorage's fire season lasts from the beginning of May through the end of September, fire risk—the potential for an intense and fast-moving wildfire–is typically greatest in May and June because those months often are dry and the year's new foliage has not yet emerged (Municipality of Anchorage 2004a).

Forest stands in the Anchorage WUI are dominated by four tree species: white spruce (*Picea glauca*), black spruce (*Picea mariana*), mountain hemlock (*Tsuga mertensiana*), and paper birch (*Betula papyrifera*). Black cottonwood (*Populus trichocarpa*) and quaking aspen (*Populus tremuloides*) are small components of some stands but are not common. Stem densities range from approximately 50–1,600 stems/ac in broadleaf stands; 30–1,200 stems/ac in mixed leaf stands; and 50–2,700 stems/ac in needleleaf stands (Cheyette 2005). Although a variety of woody shrubs and herbaceous vegetation are common, woody shrubs and grasses mostly dominate closed-canopy stands; feather mosses, ferns, and herbaceous vegetation mostly dominate open-canopy stands (Cheyette 2005).

Forest structure within the Anchorage WUI was significantly altered by a spruce bark beetle infestation in the 1990s. The infestation killed many white spruce trees and thereby modified stand composition and structure (Packee 1997, Municipality of Anchorage 2004b).

Fuels Inventory

We used a stratified random sampling design and inventoried 141 plots between June and September 2002. Our sampling protocol combined several standard sampling programs (USDA 1999, Waddell 2002). We added protocols to collect more detailed information about the live and dead surface, canopy, and ladder fuels (Figure 2). At each plot, we tallied three classes of fine woody debris and two classes of coarse woody debris along three transects and measured fuelbed height at the same locus on each transect. We also recorded the most prevalent woody shrubs and herbaceous vegetation on each plot and estimated the percent cover contributed by each. We sampled trees using a basal area prism and thereby produced a distribution of trees that could be used to estimate canopy fuel loads. Finally, we point sampled the canopy for an estimate of canopy closure.

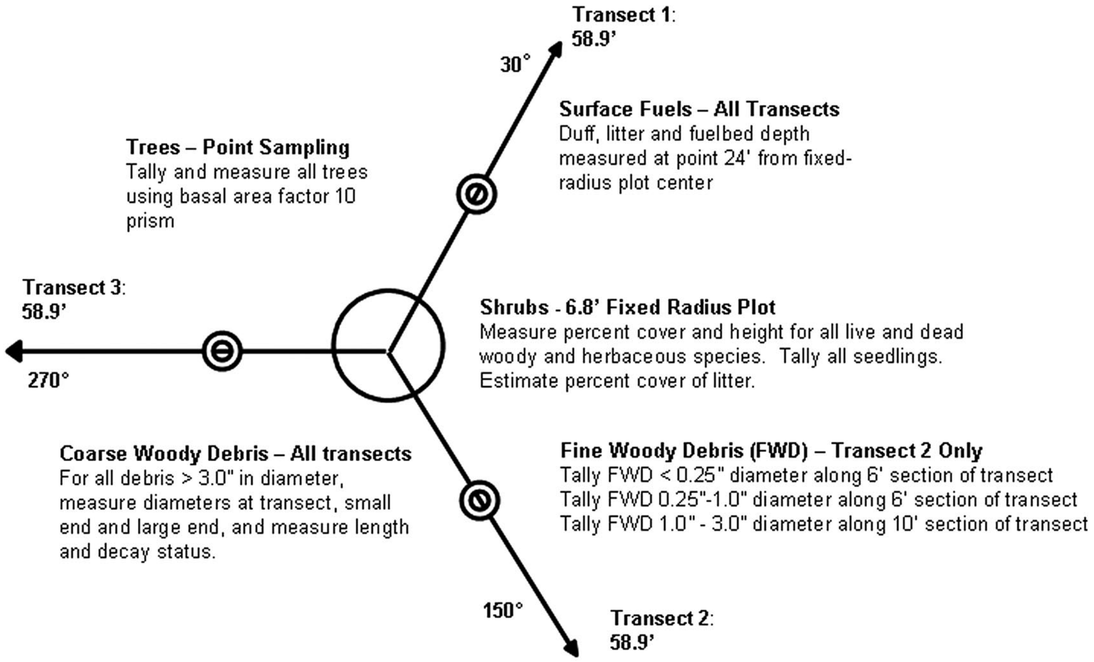

Figure 2. Field inventory protocol. Field inventory protocol is illustrated. Trees were tallied and measured around the point center using a basal area 10 prism; herbaceous surface cover and woody shrubs were tallied within a small fixed-radius plot around the point center; woody debris and duff and fuelbed depth were measured along three transects emanating from the plot center.

Fuel Model Parameters

NEXUS and the other fire behavior programs require inputs that describe the surface fuel complex (i.e., the fuel model), the canopy fuel complex (i.e., the canopy attributes), fuel moisture, weather, and terrain. Each fuel model quantifies the (1) mass per unit area ("load") for three size classes of dead fuels (1-, 10-, and 100-hour time lags) and two types of live fuels (herbaceous vegetation and woody shrubs and subshrubs), (2) the surface area-to-volume ratio for the smallest dead fuels (1-hour time lag) and the two types of live fuels, (3) the average fuelbed depth, (4) the average heat content for live and dead fuels, and (5) the average moisture of extinction beyond which fire will no longer spread (Rothermel 1983).

Average fuel loads and fuelbed depths were the main fuel model parameters defined from the inventory data. Our methodology, adopted from Brown (1974), used planar transects to tally the down woody debris and calculated load estimates from the tallies. We also followed Brown's methodology for measuring the fuelbed depth (Brown 1974).

The canopy fuel complex is defined by four attributes: total height, crown-base height, crown bulk density, and foliar moisture content. We calculated the total height and crown-base height parameters directly from the inventory data. We calculated crown bulk density using an indirect methodology, described by Alexander (1988), that relies on allometric equations to estimate the crown mass of individual trees. These masses are summed to estimate a mass per unit area (lb/ft^2) and that estimate is divided by average crown length to estimate a mass per unit volume (lb/ft^3) (Cheyette 2005).

Foliar moisture content measures the amount of water contained in the living canopy fuels and is expressed typically as a percentage of the oven-dry weight of the foliage (Van Wagner 1977). We estimated that parameter using constants based on other research (Chandler et al. 1983, Springer and Van Wagner 1984).

Fuel Type Classification

A supervised vegetation classification for the Anchorage WUI exists. That classification developed thirteen cover types that approximate the level III cover types described by Viereck et al. (1992). Anchorage fire managers previously parameterized fuel models for the dominant forest types in the Anchorage WUI using Anderson's (1982) descriptions of the thirteen standard models and Mallot's (1984) fact sheet for Alaska fuels. Four of Anderson's standardized fuel models were parameterized (models 2 [timber with grass and understory], 8 [closed timber litter], 9 [hardwood litter], and 10 [timber with litter and understory]) to create seven different fire behavior fuel models (hereinafter the "parameterized standard fuel models") (Table 1). The parameterized standard fuel models have several drawbacks: (1) they are not based on inventory data, (2) they lack detailed descriptions of the canopy fuel complex, and (3) they produce relatively indistinguishable fire predictions for multiple forest types.

Our objective was to create custom fuel models that identified statistically significant differences in forest structure (e.g., canopy closure, density, and surface fuels) and could be cross-walked to the existing vegetation classification data layer. We differentiated our inventory data into distinct forest types according to species composition, white spruce mortality, and site quality. We relied on these attributes because literature sources and fire managers widely credit them as being important determinants of fire behavior (Chandler et al. 1983, Johnson 1992). We then further differentiated forest types according to stem density (trees/ac) and basal area (ft^2/ac), quantifiable metrics that can be easily compared. We ultimately defined twenty different forest types that could be defined by eight unique custom fuel models (Table 1). Subsequent statistical analysis suggested that the forest types were unique with respect to their fuel loads and arrangements (Cheyette 2005).

Table 1. Preliminary and custom fuel model comparison.

	Ground fire parameters—Loads						Crown fire parameters—Attributes			
Forest models	1-hr (tn/ac)	10-hr (tn/ac)	100-hr (tn/ac)	Herbaceous (tn/ac)	Shrubs (tn/ac)	Fuelbed depth (ft)	Closure (%)	Height (ft)	Crown-base height (ft)	Crown bulk density (lb/ft^3)
Broadleaf forest types										
Low-density	0.50	1.50	1.00	0.15	0.15	2.80	50	60	20	0.0030
Open (standard #9)	**2.90**	**0.41**	**0.15**	**0**	**0**	**0.20**	**30**	**50**	**15**	**xxx**
High-density	0.60	1.70	2.80	0.10	0.25	1.50	80	50	25	0.0050
Closed (standard #8)	**1.50**	**1.00**	**2.50**	**0**	**0**	**0.20**	**80**	**50**	**15**	**xxx**
Mixed leaf forest types										
Low-density	0.40	1.00	0.80	0.20	0.20	2.75	50	40	10	0.0035
Open (standard #2)	**2.00**	**1.00**	**0.50**	**0**	**0.50**	**1.00**	**30**	**50**	**3**	**xxx**
High-density	0.60	1.80	1.50	0.15	0.20	1.00	70	30	10	0.0070
Closed (standard #10)	**3.00**	**2.00**	**5.00**	**0**	**2.00**	**1.00**	**80**	**50**	**3**	**xxx**
Needleleaf forest types										
Low-density spruce	0.20	0.65	1.15	0.10	0.25	2.50	15	15	1	0.0030
Open spruce (custom #1)	**2.92**	**0.41**	**0.1**	**0**	**0**	**0.20**	**30**	**50**	**2**	**xxx**
Upland black spruce	0.20	0.15	0.50	0	0.10	0.80	50	25	5	0.0040
No comparable type	**xxx**	**xxx**	**xxx**	**xxx**	**xxx**	**xxx**	**xxx**	**xxx**	**xxx**	**xxx**
Spruce hemlock	0.30	0.80	0.75	0.20	0.20	0.80	65	25	3	0.0070
Closed spruce (custom #2)	**2.92**	**0.41**	**0.15**	**0**	**0**	**0.20**	**80**	**50**	**2**	**xxx**
Beetle-killed	0.25	0.15	0.50	0.20	0.25	2.50	40	40	5	0.0050
Spruce mortality custom #3)	**2.00**	**1.00**	**0.50**	**0**	**0.50**	**1.00**	**15**	**50**	**2**	**xxx**

Rows provide NEXUS input for our custom fuel models and the parameterized standard fuel models. Rows with values in roman type are our custom fuel models; rows with values in boldface type are the corresponding parameterized standard fuel models.

Fire Behavior Modeling

We verified the utility of our custom fuel models using NEXUS simulations to compare results from our models against results for the parameterized standard fuel models. Identical weather and terrain (flat) conditions were used for each simulation. The weather scenarios included the 99th percentile weather scenario for the entire observation period fire season as well as the 50th, 90th, and 97th percentile weather scenario for the green-up (April 15th through May 31st), midsummer (June 1st through July 31st), and late-summer (August 1st through September 30th) periods. The output variables included (1) crown fraction burned (%), (2) surface fire rate of spread (chains/hour), (3) fireline intensity (Btu/ft per second), and (4) flame length (ft).

Results

The custom fuel models are substantially different from the parameterized standard fuel models (Table 1). This is particularly true with respect to 1-hour fuel loads, fuelbed depth, crown-base height, and crown bulk density. These parameter differences translated to large differences in the NEXUS results (Table 2).

Our custom fuel models have smaller 1-hour fuel loads and substantially larger fuelbed depths than do the parameterized standard fuel models. The fire behavior models use those two parameters to characterize the flash fuels that drive the flaming front of surface fires (Burgan and Rothermel 1984). The differences in these two input parameters significantly affected the predicted surface fire behavior. Our custom fuel models produced rates of spread ranging from 1 to 321 chains/hour and fireline intensities ranging from 1 to 2,549 Btu/ft per second compared with 1–70 chains/hour and 1–7,929 Btu/ft per second, respectively, for the parameterized standard fuel models. Large fuelbeds constructed primarily of bluejoint reedgrass or feather mosses—increasing fuelbed depth but not greatly increasing 1-hour fuel loads—account for these results. Bluejoint reedgrass and feather mosses are flash fuels that fuel fire spread but are consumed quickly (Sylvester and Wein 1981, Dyrness and Norum 1983).

With respect to the canopy attributes, our custom fuel models had substantially higher estimates of crown-base height than did the parameterized standard fuel models and included, for the first time, estimates of crown bulk density. These differences are significant because the fire behavior models use these two parameters to determine whether a surface fire will spread into the crowns and, if so, whether that fire spreads independent of the surface fire (Van Wagner 1977, Scott and Reinhardt 2001). Because the parameterized standard fuel models lacked crown bulk density and canopy fuel load inputs, they could be used only to predict crown fire activity linked to crown fire initiation. Our custom fuel models allowed for predictions of crown fire spread and thus provide a good deal more information regarding crown fires.

Finally, our custom fuel models predicted large and variable flame lengths but little crown burning. This suggests that surface fires are likely to burn into the canopy but are unlikely to sustain canopy fires.

Discussion

Fire Behavior Simulations

Our custom fuel models produced two types of NEXUS results. The custom fuel models describing low-density forest types produced fast-moving and intense surface fires and passive crown fire activity. This behavior is driven by deep fuelbeds dominated by bluejoint reedgrass (Cheyette 2005). The custom fuel models describing high-density forest types produced slower and less-intense surface fires that seldom cause any crown fire activity. This behavior is driven by shallow fuelbeds dominated by feather mosses (Cheyette 2005). A conclusion suggested by the results is that forest density correlates to differences in the fuel complexes that cause substantially different fire behavior predictions. The results also suggest that low-density forest types pose a greater wildfire risk to Anchorage's WUI than high-density forest types. This could be particularly true during the early spring (after snowmelt but before green-up) when bluejoint reedgrass prevalent in the low-density forest types would be cured and a potent 1-hour fuel (Roger D. Ottmar, US Forest

Table 2. NEXUS output comparison.

	All season		Green-up						Midsummer						Late summer					
	99th		97th		90th		50th		97th		90th		50th		97th		90th		50th	
Broadleaf low-density vs open deciduous																				
Crown burn	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
Rate of spread	276	**23**	189	**17**	93	**10**	17	**3**	107	**12**	56	**7**	9	**2**	125	**13**	35	**5**	5	**1**
Intensity	892	**186**	610	**141**	282	**76**	45	**19**	315	**85**	151	**47**	12	**11**	337	**85**	92	**32**	12	**7**
Flame length	10.2	**5.0**	8.6	**4.4**	6.0	**3.3**	2.6	**1.7**	6.3	**3.5**	4.5	**2.6**	1.4	**1.4**	6.5	**3.5**	3.6	**2.2**	1.4	**1.1**
Broadleaf high-density vs closed deciduous																				
Crown burn	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
Rate of spread	15	**3**	11	**2**	7	**1**	2	**1**	7	**2**	4	**1**	1	**<1**	7	**2**	3	**1**	1	**<1**
Intensity	61	**11**	46	**9**	25	**5**	6	**2**	26	**6**	15	**4**	4	**1**	23	**6**	9	**3**	2	**1**
Flame length	3.0	**1.4**	2.6	**1.2**	2.0	**1.0**	1.0	**0.6**	1.0	**1.0**	1.6	**0.8**	0.8	**0.5**	1.9	**1.0**	1.2	**0.7**	0.6	**0.4**
Mixed leaf low-density vs open mixed																				
Crown burn	21	**100**	13	**100**	2	**59**	0	**4**	2	**41**	0	**20**	0	**5**	2	**37**	0	**10**	0	**0**
Rate of spread	289	**70**	213	**57**	114	**38**	21	**10**	130	**39**	68	**26**	11	**6**	148	**42**	42	**18**	6	**3**
Intensity	1,955	**6,555**	1,183	**5,309**	425	**2,257**	61	**128**	460	**1,661**	207	**667**	30	**53**	485	**1,656**	121	**309**	15	**21**
Flame length	18.2	**70.1**	13.0	**60.9**	7.4	**26.8**	3.0	**4.2**	7.6	**19.5**	5.2	**10.2**	2.1	**2.8**	7.8	**19.0**	4.1	**6.6**	1.5	**1.8**
Mixed leaf high-density vs closed mixed																				
Crown burn	0	**100**	0	**100**	0	**67**	0	**3**	0	**48**	0	**26**	0	**0**	0	**43**	0	**11**	0	**0**
Rate of spread	15	**70**	12	**57**	7	**25**	2	**2**	7	**16**	4	**8**	1	**2**	7	**14**	3	**4**	<1	**<1**
Intensity	55	**7,929**	42	**6,425**	22	**2,047**	5	**62**	22	**1,018**	13	**348**	3	**35**	21	**799**	8	**124**	2	**18**
Flame length	2.9	**79.5**	2.5	**69.1**	1.9	**26.6**	1.0	**3.0**	1.9	**15.4**	1.4	**7.5**	0.7	**2.3**	1.8	**7.9**	1.2	**1.1**	0.6	**0.1**
Needleleaf spruce low-density vs open spruce																				
Crown burn	19	**100**	13	**100**	5	**56**	0	**0**	3	**38**	1	**15**	0	**0**	3	**38**	1	**5**	0	**0**
Rate of spread	321	**70**	229	**57**	119	**22**	22	**3**	143	**17**	73	**8**	12	**2**	165	**16**	45	**5**	6	**1**
Intensity	1,464	**6,528**	966	**5,287**	418	**1,211**	62	**19**	473	**658**	219	**165**	30	**11**	502	**591**	127	**56**	15	**7**
Flame length	15.3	**69.9**	11.8	**60.7**	7.4	**17.9**	3.0	**1.7**	7.8	**11.3**	5.4	**4.9**	2.2	**1.4**	8.0	**10.4**	4.2	**2.9**	1.6	**1.1**
Needleleaf upland black spruce vs (no preliminary fuel model to compare)																				
Crown burn	0	**xxx**	0	**xxx**	0	**xxx**	0	**xxx**	0	**xxx**	0	**xxx**	0	**xxx**	0	**xxx**	0	**xxx**	0	**xxx**
Rate of spread	40	**xxx**	29	**xxx**	16	**xxx**	4	**xxx**	19	**xxx**	11	**xxx**	3	**xxx**	21	**xxx**	7	**xxx**	2	**xxx**
Intensity	93	**xxx**	66	**xxx**	34	**xxx**	8	**xxx**	39	**xxx**	20	**xxx**	4	**xxx**	40	**xxx**	13	**xxx**	3	**xxx**
Flame length	3.6	**xxx**	3.1	**xxx**	2.3	**xxx**	1.2	**xxx**	2.4	**xxx**	1.8	**xxx**	0.9	**xxx**	2.4	**xxx**	1.5	**xxx**	0.7	**xxx**
Needleleaf spruce-hemlock vs closed spruce																				
Crown burn	63	**100**	14	**100**	0	**47**	0	**0**	0	**32**	0	**5**	0	**0**	0	**28**	0	**0**	0	**0**
Rate of spread	50	**70**	19	**57**	7	**18**	2	**2**	1	**12**	4	**5**	1	**1**	7	**11**	3	**3**	<1	**<1**
Intensity	832	**6,528**	111	**5,287**	18	**843**	4	**12**	18	**420**	10	**50**	2	**8**	16	**340**	6	**18**	1	**5**
Flame length	14.8	**69.9**	4.0	**60.7**	1.7	**13.7**	0.8	**1.4**	107	**8.5**	1.3	**2.7**	0.6	**1.2**	1.6	**7.5**	1.0	**1.7**	0.5	**1.0**
Needleleaf spruce beetle–killed vs spruce mortality forest																				
Crown burn	45	**100**	31	**100**	11	**60**	1	**6**	7	**40**	3	**21**	0	**2**	7	**38**	1	**12**	0	**0**
Rate of spread	175	**70**	140	**57**	80	**38**	15	**10**	93	**38**	49	**25**	8	**6**	105	**41**	30	**18**	4	**3**
Intensity	2,549	**6,679**	1,552	**5,410**	476	**2,322**	45	**143**	447	**1,649**	179	**668**	21	**56**	470	**1,708**	94	**333**	10	**21**
Flame length	25.9	**70.9**	17.4	**61.6**	8.2	**27.5**	2.6	**4.5**	7.7	**19.4**	4.9	**10.3**	1.8	**2.9**	7.9	**19.5**	3.6	**6.9**	1.3	**1.8**

Columns compare NEXUS output for the custom and preliminary fuel models across 10 different weather scenarios: the 99th percentile weather scenario for the entire season and the 97th, 90th, and 50th percentile weather scenarios for the green-up, midsummer, and late-summer periods. Output variables reported include percent crown burned (%), rate of spread (chains/hr), fireline intensity (Btu/ft per sec), and flame length (ft). Columns with values in roman type contain output for our custom fuel models; columns with values in boldface type contain output for the parameterized standard fuel models. As is explained in the text, percent crown burned calculations for our custom fuel models includes crown fire spread; calculations for the parameterized standard fuel models includes only crown fire initiation.

Service Lab, person communications, Jan. 3, 2007). Some observers have, nevertheless, noted extreme fire behavior in high-density stands in low humidity (less than 40%) and high-wind situations. Under those conditions, fire that might otherwise be characterized by short flame lengths and confined to the surface can rise up into the crowns and sustain a crown fire in the dense canopies (Roger D. Ottmar, US Forest Service Lab, person communications, Jan. 3, 2007).

We encountered a large amount of spruce bark beetle impacted acreage in the WUI. The recent infestation affected more than 3.2 million ac in Alaska and 85,000 ac within Anchorage (Packee 1997, Municipality of Anchorage 2004b). The impacts of such infestations can be profound—causing extensive tree mortality, reducing stand density, and adding large quantities of woody debris to the forest floor (Packee 1997, Holsten et al. 1999). Our NEXUS results for the needleleaf beetle-killed forest types confirm that the spruce bark beetle infestation created a dangerous landscape. This forest type combines a large and highly flammable surface fuel complex (largest flame lengths and fireline intensities and third fastest rates of spread) with a substantial canopy fuel complex (most crown fire activity for a majority of weather scenarios) (Table 2). NEXUS predicted rapidly spreading and intense surface fires that are likely to initiate crown fire activity. No other forest type presented this dangerous combination.

The parameterized standard fuel models have several flaws. First, the parameterized standard fuel models differentiated several forest types solely by two canopy attributes: total height and crown-base height. NEXUS results show that crown fire activity is not likely during most weather scenarios. Under those circumstances, NEXUS results will be indistinguishable for multiple models. Second, the parameterized standard models led to some apparently incongruous NEXUS results. The mixed leaf open and closed fuel models produced more extreme NEXUS results than did the needleleaf fuel models and nearly as extreme output as the needleleaf beetle-killed fuel model. Given the forest structure, composition, and fuel loads of these forest types, we would expect the mixed leaf forest types to produce less extreme NEXUS results. This incongruity occurred because the parameterized standard fuel models used to describe mixed leaf stands overestimated the 1-hour fuel loads and the parameterized standard fuel models used to describe needleleaf stands underestimated fuelbed depths.

Management Implications

Our custom fuel models are a significant improvement over the parameterized standard fuel models. NEXUS results for the custom fuel models make sense in light of the inventory results and most preconceptions up to this time held regarding fire behavior for the Anchorage WUI. We are not aware of any other studies that have successfully used inventory data to create custom fuel models and our research builds on the prior modeling efforts of Mallot (1984) and Norum (1982).

Despite the apparent efficacy of our custom fuel models, they have some faults that necessitate further research and merit discussion here. With few exceptions, our custom fuel models have considerably smaller 1-hour fuel loads than the parameterized standard fuel models (5–10 times smaller) but much larger fuelbed depths (2–10 times larger). These differences impact the NEXUS output. The 1-hour fuels (grasses, mosses, and fallen twigs) drive the flaming front of surface fires (Sylvester and Wein 1981, Dyrness and Norum 1983). Fires will consume these fuels rapidly so long as they are not too tightly packed, i.e., a sufficiently large fuelbed depth (Burgan and Rothermel 1984). Conversely, small fuelbed depths mean a more compact fuel complex that supports slower spreading fires (Burgan and Rothermel 1984). Owing to their smaller but more oxygenated 1-hour fuel loads, the custom fuel models give rise to considerably faster-moving fires. The rates of spread predicted by NEXUS are consistently 5–10 times faster for those models.

Our inventory did not quantify the live or dead herbaceous component of the 1-hour fuel complex. Rather, we relied on phytomass estimates from the Susitna River Basin Study (USDA 1986) to quantify the loads of bluejoint reedgrass in low-density forest types and the loads of feather mosses in high-density forest types. Researchers have concluded that these grasses and mosses will readily desiccate and act as a flash fuel (Sylvester and Wein 1981, Dyrness and Norum 1983, Cheney et al. 1998). Accordingly, it is important to quantify accurately the fuel loads contributed by these species. Although several methods exist to quantify these fuels (Burgan and Rothermel 1984, Yarie and Mead 1988), those methods are labor- and time-intensive and were well beyond the scope of our research. Future efforts are needed to measure directly these loads to insure model accuracy.

We also relied on species tally information from our inventory and phytomass data from the Susitna River Basin Study (USDA 1986) to estimate the live fuel loads of herbaceous plants and woody shrubs. The surface fire simulation algorithms used in NEXUS and other fire behavior models include live fuel loads of herbaceous plants and woody shrubs in the fuel complex. These fuels are initially treated as heat sinks that, when sufficiently heated from dry fuel combustion, can contribute to a fire's intensity (Burgan and Rothermel 1984). Our eight custom fuel models had small and similar loads of live herbaceous and woody fuels. This contrasted from the parameterized standard fuel models, which mostly ignored the live fuels component to the fuel complex.

Our custom fuel models potentially overestimate fuelbed depth. Fuelbed depths are considerably larger in our custom fuel models for all but the mixed leaf high-density forest type. We relied on a methodology described by Brown (1974) that estimates average fuelbed depth as 70% of the height of the tallest vegetation measured. An overestimate could occur where these heights are skewed by tall shrubs or uncharacteristic vegetation at the point of measurement. Any overestimate of fuelbed depth would give rise to inflated predictions of rate of spread (Chandler et al. 1983, Burgan and Rothermel 1984). Future inventory efforts are needed to verify the accuracy of our measurements.

The parameterized standard fuel models do not define crown bulk density. This shortfall is avoidable because crown bulk density can be estimated using allometric equations for crown mass (Cheyette 2005). The most difficult and critical step to this approach is finding appropriate equations. Researchers (Singh 1986) and common sense suggest that there are rather large variations between equations and, as a result, a potential to incorrectly estimate this parameter. Nevertheless, our crown bulk density estimates appear within the range of crown bulk density estimates calculated by researchers for other forests (Van Wagner 1977, Scott and Reinhardt 2002).

Several questions regarding our custom needleleaf beetle-killed fuel model warrant further inquiry. First, the fuel model's potent surface fire component results from the assumption that bluejoint reedgrass dominates the 1-hour fuel complex as it does in the needleleaf spruce low-density model. Although other research (Holsten et al. 1995) and our inventory results support this assumption, further research is needed to quantify the amount of bluejoint reedgrass present. Second, the needleleaf beetle-killed fuel model has a relatively heavily loaded canopy fuel complex because many of the dead spruce trees remain standing and have not shed their fine branches after death (Holsten et al. 1995, Packee 1997). Eventually, these spruce trees will lose their branches and will no longer augment the canopy fuel complex. How long this will take is unknown and justifies further monitoring.

Future Needs

As with any modeling effort, further refinements are always possible. Our models would benefit from data that quantifies the phytomass of the herbaceous and woody fuel loads (particularly bluejoint reedgrass and feather mosses) in each forest type and from research that more fully explains how fuel loads in the spruce and mixed leaf forest types are changing as a result of the spruce bark beetle–induced tree mortality. In addition, fire managers need to verify the accuracy of the NEXUS results for our custom fuel model simulations. They must evaluate whether the NEXUS results mimic the expected fire behavior for the Anchorage WUI landscape. This also will answer the ultimate question: do our custom fuel models adequately describe the landscape of the Anchorage WUI and lead to robust fire behavior predictions?

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