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Characterizing fuels in the 21st Century

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Abstract. The ongoing development of sophisticated fire behavior and effects models has demonstrated the need for a comprehensive system of fuel classification that more accurately captures the structural complexity and geographic diversity of fuelbeds. The Fire and Environmental Research Applications Team (FERA) of the USDA Forest Service, Pacific Northwest Research Station, is developing a national system of fuel characteristic classification (FCC). The system is designed to accommodate researchers and managers operating at a variety of scales, and who have access to a variety of kinds of input data. Users can generate fuel characteristics by accessing existing fuelbed descriptions (fuelbed prototypes) using generic information such as cover type or vegetation form. Fuelbed prototypes will provide the best available predictions of the kind, quality and abundance of fuels. Users can accept these default settings or modify some or all of them using more detailed information about vegetation structure and fuel biomass. When the user has completed editing the fuelbed data, the FCC system calculates or infers quantitative fuel characteristics (physical, chemical, and structural properties) and probable fire parameters specific to that fuelbed. Each user-described fuelbed is also assigned to one of approximately 192 stylized fuel characteristic classes.

Keywords: fuel classification, fuel models, fuel characteristics, FCC, fire management, fire modeling, fire behavior, fire effects, United States, Alaska.

Introduction

The development of spatial fuel property layers is one of the most important tasks required to operate fuel and fire management decision support systems and dynamic vegetation models. Knowledge of wildland fuelbed characteristics has always been important to fire managers, and is becoming increasingly important to ecologists, air quality managers, and carbon balance modelers. As the source of all fire behavior and fire effects, fuelbeds must be characterized and mapped before any calculation of fire potential can be made. Fuel mapping, hazard assessment, evaluation of fuel treatment options and sequences, and monitoring fire effects all require a consistent and scientifically applied fuel classification system.

It would be prohibitively difficult to inventory all fuelbed characteristics each time it became necessary to predict events or to make management decisions. Fuelbeds are structurally complex, vary widely in their physical attributes, and vary in their potential fire behavior and effects as well as in the options they present for fire control and use. The extreme variation in fuelbed characteristics is not chaotic, but rather is the expression of ecological processes working over time, of natural disturbance events, and of human manipulation. Some orderly method of classifying fuels and inferring fuelbed properties from limited observations is needed. We need a classification and characterization scheme that serves a variety of users, simplifies the complexity to a reasonable degree, but does not oversimplify the description of wildland fuelbeds. We present the design of a system of fuel characteristic classes. Our objective in designing the fuel characteristic class system (FCC) is to provide fuel managers with a nationally consistent and durable system to classify fuelbeds and to provide numerical inputs to fire behavior, fire effects, and dynamic vegetation models.

We begin this paper with a review of the approaches taken to classify fuels in the 20th Century in the United States, culminating in the widespread use of stylized fuel models. This is followed by a discussion of the need for a more

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extensive and robust system to satisfy the range of user needs not served by current fuel models. We describe the concept and design of FCC system in detail.

Review of past approaches

For 80 years, fire control planning has been the singular driving purpose for classifying fuels in the United States. The primary focus of fuel classification efforts has been on rating the potential rate of spread or rate of perimeter increase from an initiating fire so that initial attack response time could be designed to contain the fire at a reasonable size. Show and Kotok (1930) used the concept of 'hour control zones' to classify vegetation cover types by how quickly initial attack must be made on a fire after its start in order to achieve an acceptable probability of control. The system remained in use for two decades but was judged too arbitrary because it ignored the variability in fire hazard within cover types, especially where human or natural change agents had occurred (Brown and Davis 1973).

The secondary consideration when classifying fuels has been how difficult a potential fire would be to suppress. Hornby's (1936) approach was to classify fuels both by their potential rate of spread and the 'resistance to control' under 'average worst' burning conditions. Average worst conditions were defined as burning conditions typical of the worst part of the average fire season. Rate of spread was estimated by statistical analysis of individual fire reports, and resistance to control was estimated by measuring the amount of time needed to construct fireline by hand. Each measure was assigned a descriptive class—low, medium, high, and extreme. Later studies by Barrows (1951) added a fifth class, 'flash', to the rate of spread in fine grasses and fresh logging slash. Hornby's system remained the standard for about 40 years, and was widely used to map fuels until the 1970s. The weaknesses of the 'resistance to control' approach were that it was tied only to handline construction, it was limited to an initiating fire, and it did not consider crowning or other severe fire behavior (Brown and Davis 1973). The classification is still in use, and has been updated to include line production rates for indirect and aerial attack.

Development of a mathematical spread model (Rothermel 1972) that allowed consideration of the intensity and rate of spread of initiating fires in reasonably homogenous fuels modernized fire behavior prediction systems, because it allowed consideration of the intensity and rate of spread of initiating fires in reasonably homogeneous surface fuels. Fire prediction systems based on the model have continued to focus on the rate of spread, but replaced resistance to control with flame length as the primary measure of suppression effort required. The model quickly became the most widely used method to predict fire behavior, and remains so today. Decision support systems such as Fire Family (Andrews and Bevins 1999), Nexus (Scott 1999), Farsite (Finney and Andrews 1999), and the National Fire Danger Rating System (Deeming *et al.* 1977) are all based on Rothermel's fire spread model.

Availability of the spread model greatly increased the demand for quantitative fuels data. Brown's (1974) line-intersect fuels inventory was widely adopted in the 1970s to quantify fuel loading inputs, and is still in use when precision is required or no knowledge is available to infer fuel loadings from observations. However, the method is tedious and expensive, and results usually cannot be input directly into the spread model without adjustment (Burgan and Rothermel 1984). Photo series (Ottmar and Vihnanek 1998) have been developed in many fuel types to overcome the difficulty and expense of fuels inventory, but the problem of requiring adjustment of the inventory values remains.

Thirteen stylized fuel models (Albini 1976) were developed to provide standardized numerical fueldbed descriptions in order to generate reasonable and accurate fire behavior predictions using the spread model. Each model is a small database of about 30 fuelbed properties that determine its fire behavior potential. The models were conceived of as a set of standardized and stylized inputs for use in the spread model across the range of fire behavior commonly seen in surface fuels. Because they are tailored to a specific numerical processor, they do not include the inputs for many other models and assessments. Their significant value is in the quality of fire behavior predictions that result from their use. That usefulness extends to predicting fire effects such as scorch height, which is a function of fireline intensity. Limiting the number of stylized fuel models to 13 has made them easy to visualize as a set and to communicate within the fire community. Most fire managers have the fuel models memorized, or they carry a small set of aids (nomograms, wallet cards, and others) that facilitate rapid calculation of expected fire behavior.

Stylized fuel models were meant to approximately represent fuelbed properties found in nature. The standard 13 models do not include forest floor depth or load or any measure of large woody fuels as these are not required inputs to Rothermel's models. They were not designed to be correlated with actual fuel loadings, vegetation cover, remote-sensing signatures, or modeled ecosystem dynamics. Nonetheless, Anderson (1982) provides a key to assigning fuel models by cover type. Many fire managers and modelers have used Anderson's key to infer physical properties such as fuel loading, to assess flammability, and to estimate biomass combustion. Large errors can be expected from such estimates.

New generations of fire behavior models will also require different fuelbed characterizations than are available from current fuel models. The current fire behavior models are not particularly useful for predicting fire effects that are dependent on fire residence time, such as soil or cambium heating, or effects on the atmosphere such as air pollutant or carbon release that depend on biomass consumption. Many

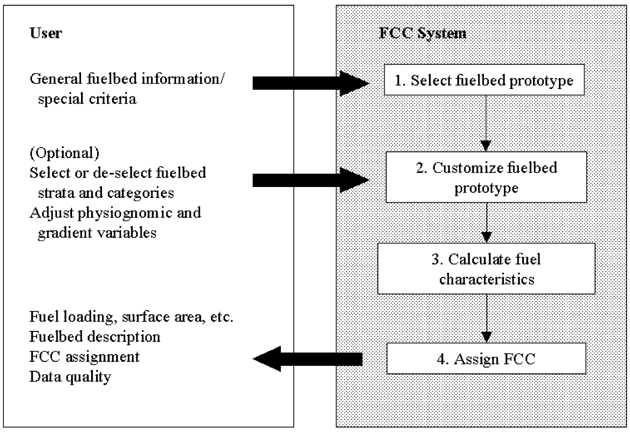

Fig. 1. User-provided general fuelbed information identifies a fuelbed prototype. The prototype identifies the kinds of fuel present (fuelbed strata and categories) and their qualitative (physiognomy) and quantitative (gradient variables) features. The user can then adjust the prototypic information. Next, the system calculates fuel properties and fire parameters based on the customized fuelbed data. Finally, the system assigns the fuelbed to a stylized Fuel Characteristic Class.

authors (for example, Andrews and Bevins 1999; Scott 1999; Keane *et al.* 2001) have pointed out the limitations of 13 fuel models, and have encouraged development of a comprehensive fuel classification system.

Between 1995 and 1999, the Fire Emissions Tradeoff Model (FETM) (Schaaf 1996) was developed to demonstrate the tradeoffs between wildfire and prescribed fire emissions and the Interior Columbia River Basin Assessment was underway (Ottmar *et al.* 1998). Both efforts required a more robust way to assign fuel loadings across the landscape than the 13 fire behavior models could provide. The fuel condition classes (Schaaf 1996; Ottmar *et al.* 1998) were developed to improve fuel loading assignments. The fuel condition class system was the forerunner of the fuel characteristic class system.

In summary, fuel classification for most of the 20th Century focused primarily on the rate of spread, resistance to control, and the flame length of initiating fires in surface fuels. This focus ably served the need for fire suppression planning and has become increasingly quantitative as tools for numerical assessment of hazard become available. Thirteen stylized fire behavior models have been widely and effectively used in this context. However, this focus has not addressed the needs to predict extreme fire behavior or model fire behavior and effects related to the residence time, persistence, or the total heat release (biomass consumption) from fires. The existing fuel models do not accurately characterize the actual fuel character and variability found in nature. These 13 models will always be useful to fire managers using the current generation of fire behavior models. In the foreseeable future, fuel classification systems should include a seamless cross-reference to the stylized set of 13 fuel models.

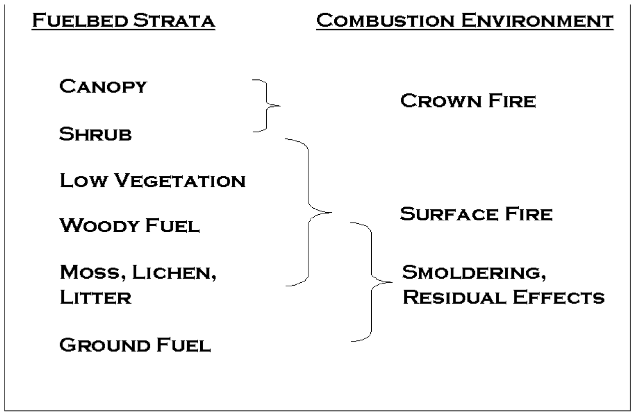

Fig. 2. Fuelbed strata as combustion environments.

Comprehensive fuelbed classification

The Fire and Environmental Research Applications Team (FERA) of the USDA Forest Service, Pacific Northwest Research Station, is currently developing a national system of fuel characteristic classification (FCC) with funding from the Joint Fire Science Program. The major criteria for system design include:

1. Applicability throughout the United States;
2. Accommodation of a wide range of potential users, operating at different scales, with various levels of detail, quality and quantity of data.

The general design of the FCC system (Fig. 1) allows users to access existing fuelbed descriptions (fuelbed prototypes) or modify existing descriptions to create custom fuelbeds. The user can select a fuelbed prototype using cover type or other vegetation classification information. The selected prototype provides the best available predictions of the kinds of fuel (fuelbed strata and categories) and their quality (physiognomy) and relative abundance (gradient variables). The user can accept these default settings or modify some or all of them using site-specific knowledge. When the user has completed editing the qualitative and quantitative fuelbed data, the FCC system calculates quantitative fuel characteristics (physical, chemical, and structural properties) and probable fire parameters specific to the fuelbed in question. Each user-described fuelbed is also assigned to one of approximately 192 stylized fuel characteristic classes.

A general fuelbed model

Fuelbeds are complex in structure, and diverse in their physical attributes and the biological origin of their components. A comprehensive system of fuels characterization requires a fuelbed model that captures this diversity. The model presented here stratifies fuelbeds into six horizontal fuelbed stata that represent unique combustion environments (Figs 2 and 3). The use of fuelbed strata

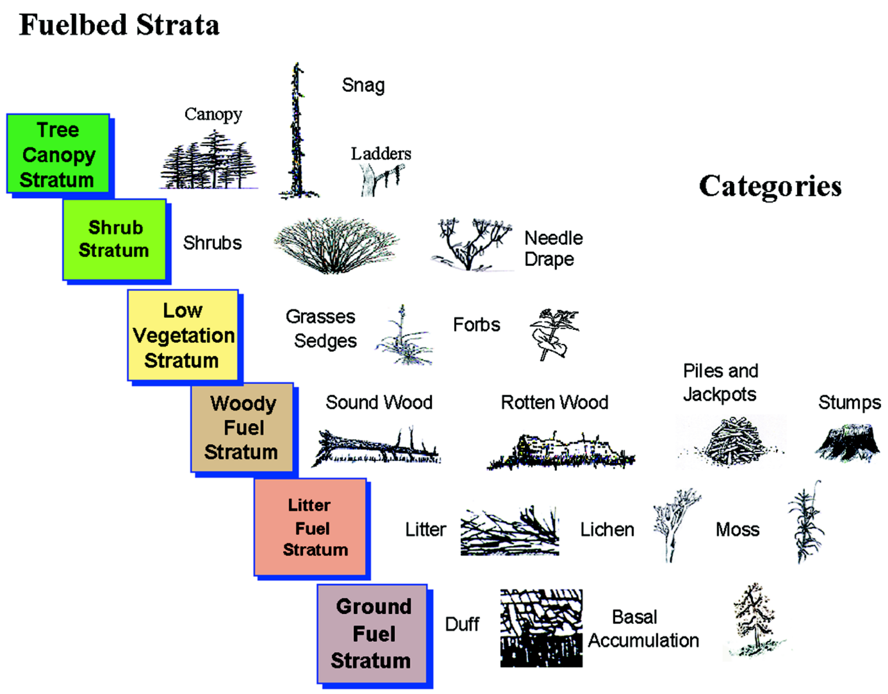

Fig. 3. Fuelbed strata and categories.

facilitates the creation of spatial data layers and allows the user to include, combine, or exclude as much detail as is needed to suit a particular use.

Each fuelbed stratum is broken into one or more fuel types, with common combustion characteristics, called fuelbed categories (Table 1; Fig. 3). The low vegetation stratum, for example, includes a grass/sedge category and a forb category. There are 16 fuelbed categories in total.

Each fuelbed category is described by physiognomic and gradient variables. Physiognomic variables capture qualitative features of the category, including morphological, chemical and physical features. The grass and sedge category includes physiognomic variables for leaf blade thickness (which is used to infer surface-area-to-volume ratio) and growth habit (which is used to infer the spatial distribution of fuel). Where physiognomic criteria are based on vegetation features, the system includes species lists that provide the physiognomic information. The user is asked to provide either a species name or the physiognomic information.

Gradient variables characterize the relative abundance of fuel. The grass and sedge category includes the gradient variables of percentage cover, height, and percentage live (of total biomass). With these estimates of fuel character (physiognomic variables) and abundance (gradient variables), the system calculates total fuel loading, fuel surface area and other parameters required as inputs by fire models.

Fuelbed prototypes

The FCC system provides a set of prepared fuelbed descriptions or prototypes. These fuelbed prototypes are designed to include most major fuelbed types throughout the United States and represent a loose classification of vegetation type (vegetation form and cover type) and of fire potential (fire effects and behavior). Fuelbed prototypes provide default information about the fuelbed categories present and their physiognomic and gradient variables. Fuelbed prototypes are based on the best available published and unpublished data. Default information can be modified by selecting additional categories or deselecting categories, and by adjusting physiognomic and gradient variables when more site-specific data is available.

Users can access fuelbed prototypes with only limited or partial general fuelbed information. The FCC system will allow authorized users to add new fuelbed prototypes to the system database so that the system may learn to make finer distinctions over time. The general fuelbed information used to organize the fuelbed prototypes will include:

- Ecoregion division (Bailey 1997): Fuelbed prototypes are organized geographically to improve prototype selection when only very general information such as vegetation form is available.
- Vegetation form: Vegetation form describes the gross physiognomic structure of a landscape unit. Options include conifer forest, hardwood forest, mixed forest, shrubland, grassland and savanna. Coupled with a choice of ecoregion division, the system provides the user with a pull-down menu of all the conifer forest prototypes available for a certain division. Vegetation form can also be used with remote sensing data where only very general information about vegetation is available.

Table 1. Fuelbed strata and categories, and their physiognomic and gradient variables

Fuelbed strata	Fuelbed categories	Physiognomic variables	Gradient variables
Canopy	Tree	Canopy structure	Canopy height
		Crown type	Height to live crown
			Percentage cover
	Snag	Snag class	Diameter
			Height
			Snags per acre
	Ladder fuels	Vegetation type	Significance
Shrub	Shrub	Foliage type	Percentage cover
		Growth habit	Height
		Accelerant potential	Percentage live vegetation
	Needle drape		Significance
Low vegetation	Grass/sedge	Leaf blade thickness	Percentage cover
		Growth habit	Height
			Percentage live vegetation
	Forb		Percentage cover
			Height
Woody fuel	Sound wood	Size class	Loading (tons/acre)
			Fuelbed depth
	Rotten wood	Size class	Loading (tons/acre)
	Stumps	Decay class	Stems/acre
			Diameter
	Woody accumulations	Piles, windrows or jackpots	Height
		Clean or dirty	Width
			Length
			Number/acre
Moss/lichen/litter	Moss	Moss type	Percentage cover
			Depth
	Lichen		Percentage cover
			Depth
	Litter	Litter Type	Percentage cover
		Litter Arrangement	Depth
Ground fuel	Duff	Character	Depth
			Percentage rotten wood
	Basal accumulation	Accumulation type, e.g. litter, bark slough	Depth
			Trees per acre affected

- Cover type: The FCC system uses a synthetic classification of cover type based on dominant vegetation and fire potential, but crosswalks to existing cover type classifications whenever possible (e.g. Eyre 1980; Shiflet 1994).
- Structure class: Structure class applies mainly to forests and captures the number of canopy layers, the relative size of trees, the stage of development of the understory and the relative degree of stand closure. Descriptions of vegetation structure are used to fine-tune the categories present and the partitioning of fuels in canopy layers.
- Change agent: Change agent refers to activities such as fire suppression, insect and disease mortality, wind and timber harvesting that significantly alter fuelbeds. Fuelbed prototypes reflect a range of possibilities.

Output: Fuel characteristics and fuel characteristic classes

The FCC system has the ability to provide users with continuous fuel characteristics, based on user input, and a stylized fuel characteristic class. Several different output formats will be available, but a complete output file includes:

- Fuelbed name and description as provided by the user;
- All input information provided by the user or inferred by the FCC system;
- All fuel characteristics generated by the system including fuel loading, fuel surface area;
- Fuel Characteristic Class assignment (see Fig. 4 and information below);
- National Fire Danger Rating System (NFDRS) and Northern Forest Fire Laboratory (NFFL) fuel model assignments; and
- Reliability or data quality index.

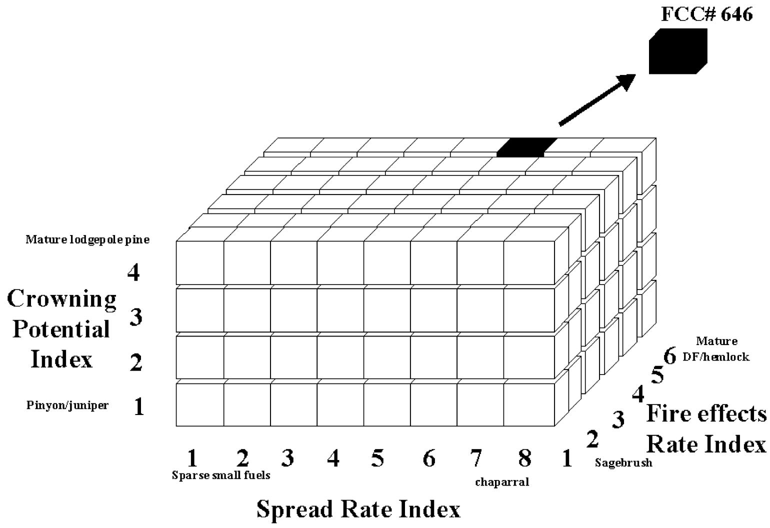

Fig. 4. 192 stylized fuel characteristic classes in 3-dimensional space grouped by three critical attributes of spread rate, crowning potential, and fire effects.

Fuel characteristics are calculated or inferred using the best available published data and, where necessary, unpublished information. This information includes biomass equations, photo series and other published fuels data, and relationships between physiognomic features and physical parameters such as surface-area-to-volume ratio, bulk density, and flammability. This information is stored in an FCC catalog with a rule base that links information to the appropriate fuelbed.

Generating continuous fuel characteristics specifically for the fuelbed in question creates several problems:

1. It limits the ability of users to communicate and compare fuelbeds; and
2. Many fire models require stylized input data that must be calibrated to generate appropriate model behavior.

To address these issues, the FCC system includes a set of stylized fuel characteristic classes based on three key attributes (Fig. 4):

1. Index of potential spread rate or reaction intensity;
2. Index of crowning potential; and
3. Index of fire effects based on biomass consumption and residence time.

The FCC number assigned to each fuelbed indicates the level of each index. FCC#743 will have a spread rate index of 7, a crowning potential index of 4 and a fire effects index of 3.

Implementation

A series of workshops with fuels experts and potential users of the system was held around the United States to ensure regional applicability of the system. Initial system design is complete and we are proceeding with database and user-interface engineering, and collation of data to populate the FCC system. The user interface is in the design phase and will allow users to access fuel characteristics in several ways:

- Select a fuelbed prototype based on general fuelbed information and accept default fuel characteristics;
- Select a fuelbed prototype and modify the default settings based on site-specific knowledge;
- Create custom fuelbeds (and custom fuelbed databases);
- Search existing fuelbed prototypes by specific criteria (for example, spread rate index); or
- Work in batch mode where the FCC system will read a file containing polygon or inventory attribute data and generate fuel characteristics for each data record.

Efforts are also underway to ensure that the FCC system will link with existing fire and landscape assessment models. Linkages with FFE-FVS (Fire and Fuels Extension to the Forest Vegetation Simulator), CONSUME (model that predicts fuel consumption and emissions), Fire Effects Tradeoff Model (a model to evaluate the tradeoffs between wildfires and prescribed fires), and FASTRAC (a database model designed to compile fuels information) are currently in progress. Additional linkages to other fire models such as Behave, Farsite, and FOFEM, are anticipated.

A prototype of the FCC system will be available for beta testing by the end of 2001 and the system will be fully operational by 2003. The FCC system is designed to learn. Data quality will be indexed and protocols will be in place to append new information and replace inaccurate information. The objective is to provide fuels data to a large number of people over a broad geographic area and create a system that may eventually have international applicability. The FCC system will be adaptive and respond to the needs and input of users.

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