Quantifying physical characteristics of wildland fuels using the Fuel Characteristic Classification System[1]

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Abstract: Wildland fuel characteristics are used in many applications of operational fire predictions and to understand fire effects and behaviour. Even so, there is a shortage of information on basic fuel properties and the physical characteristics of wildland fuels. The Fuel Characteristic Classification System (FCCS) builds and catalogues fuelbed descriptions based on realistic physical properties derived from direct or indirect observation, inventories, expert knowledge, inference, or simulated fuel characteristics. The FCCS summarizes and calculates wildland fuel characteristics, including fuel depth, loading, and surface area. Users may modify fuelbeds and thereby capture changing fuel conditions over time and (or) under different management prescriptions. Fuel loadings from four sample fuelbed pairs (i.e., pre- and post-prescribed fire) were calculated and compared by using FCCS to demonstrate the versatility of the system and how individual fuel components, such as shrubs, nonwoody fuels, woody fuels, and litter, can be calculated and summarized. The ability of FCCS to catalogue and summarize complex fuelbeds and reflect dynamic fuel conditions allows calculated results to be used in a variety of applications including surface and crown fire predictions, carbon assessments, and wildlife habitat management.

Résumé : Les caractéristiques des combustibles en milieu naturel sont utilisées dans plusieurs applications de prédiction opérationnelle des incendies ainsi que pour comprendre le comportement et les effets du feu. Il y a quand même un manque d'information sur les propriétés fondamentales des combustibles et leurs caractéristiques physiques en milieu naturel. Le système de classification des caractéristiques des combustibles (SCCC) permet d'élaborer et de cataloguer les descriptions des couches de combustibles sur la base de propriétés physiques réalistes dérivées de l'observation directe ou indirecte, de relevés sur le terrain, de la connaissance d'experts, par déduction ou à partir de caractéristiques simulées des combustibles. Le SCCC résume et calcule les caractéristiques des combustibles en milieu naturel, incluant l'épaisseur, la charge et la surface des combustibles. Les utilisateurs peuvent modifier les couches de combustibles et de ce fait saisir l'état des combustibles qui change avec le temps et à la suite de différentes prescriptions d'aménagement. La charge de combustibles associée à quatre paires de couches de combustibles (c.-à-d. avant et après un brûlage dirigé) a été calculée et comparée à l'aide du SCCC pour démontrer la versatilité du système et de quelle façon les composantes individuelles des combustibles telles que les arbustes, les combustibles non ligneux, les combustibles ligneux et la litière peuvent être calculées et résumées. La capacité du SCCC à classer et synthétiser des couches complexes de combustibles et à refléter l'état des combustibles de façon dynamique permet de calculer des résultats utilisables dans une variété d'applications incluant la prédiction des feux de cime et de surface, l'évaluation du carbone et la gestion de l'habitat de la faune sauvage.

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Introduction

The Fuel Characteristic Classification System (FCCS) (Ottmar et al. 2007) was developed to provide a systematic catalogue of fuel characteristics that allows users such as land managers, policy makers, and scientists to accurately represent and quantify wildland fuels. FCCS facilitates the designation of fuel characteristics and fire hazard potential to landscapes across the United States and is composed of three elements: (1) a library of FCCS fuelbeds that can be evaluated and customized in a user-friendly interface (Riccardi et al. 2007), (2) calculation of summary fuel characteristics, the subject of this paper, and (3) calculation of potential fire behaviour and fire effects (Sandberg et al. 2007*a*, 2007*b*).

Characterization of wildland fuels has typically focused on assessing fire behaviour or fire danger by supplying inputs to mathematical models to guide tactical fire management decisions (Sandberg et al. 2001). In Canada, fuels generally are characterized by using standard fuel types to support the Canadian Forest Fire Danger Rating and Fire Behaviour Prediction systems (Forestry Canada Fire Danger Group 1992; Taylor et al. 1997). In the United States, stylized fuel models are used in the National Fire Danger Rating System (Deeming et al. 1977) and applications of a surface

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fire spread model (Rothermel 1972; Burgan 1987). A review of previous fuel classification systems is provided in Sandberg et al. (2007*a*).

Fire behaviour fuel models are not necessarily intended to represent realistic fuelbed measurements but are tuned to provide reasonable fire behaviour predictions using the Rothermel (1972) spread model. Albini (1976) refined the initial 11 fuel models and added two, creating 13 fuel models for broad application. Anderson (1982) described the 13 fuel models, provided aids to selecting a fuel model, and developed a key to link fire behaviour fuel models with the fire danger rating system fuel models of the National Fire Danger Rating System (Deeming et al. 1977). Other fuel models were developed for specific applications such as palmetto–gallberry (Hough and Albini 1978) and California chaparral (Kessell and Cattelino 1978). Scott and Burgan (2005) defined an additional 43 fuel models for use with the Rothermel surface fire spread model. Models for homogeneous (i.e., uniform fuel size and arrangement) and spatially uniform (i.e., continuous and nonvariable) surface and canopy fuels have been well established (Rothermel 1972; Van Wagner 1977; Rothermel 1991) and used in computer applications (Andrews 1986; Andrews and Chase 1989; Finney 1998; Beukema et al. 1999) to support fire management decisions. Relatively simple bulk fuelbed characteristics are adequate as inputs to the models, which are designed to reflect the sensitivity of fire behaviour to variable fuel characteristics and environmental conditions.

Wildland fuelbeds are in reality far from homogenous and are often defined by the physical components (e.g., loading, size, and bulk density) of live and dead fuels that occur on a site or contribute to wildland fire (Davis 1959; Anderson 1982). Early fuel descriptions consisted of qualitative measures and focused on logging slash, whereas later efforts became more quantitative, with increasing emphasis on wildland fuels (Warren and Olsen 1964; Van Wagner 1968; Brown and Roussopoulos 1974; Ottmar et al. 2004).

One of the key shortcomings of previous fuel characterizations is that they did not necessarily represent realistic fuel conditions. The need for realistic and comprehensive information on wildland fuel characteristics and properties is not limited to fuel models and fire behaviour prediction. Wildland fuel characteristics also are critical for modeling fire effects (Reinhardt 2003) including smoke production and emissions (Ottmar et al. 1993) and for ecosystem management planning including wildlife habitat assessments (Maser et al. 1979) and carbon inventories (Houghton et al. 2000).

In this paper, we discuss the assumptions and calculations made to process raw fuels data into summary information that describes fuelbeds and fuelbed components in terms useful for interpreting potential fire behaviour, fire effects, environmental consequences, and ecosystem functions of fuels. We also provide a sample case study in which FCCS is used to assess fuel characteristics before and after a fuels reduction project, which highlights the systems ability to record and summarize fuel characteristics under different management scenarios. Throughout the paper, we define a fuel characteristic as an extrinsic fuel property, referring to the physical dimension or condition of fuels such as height, moisture content, and depth. Fuel characteristics change temporally and spatially in response to weather, climate, or other disturbances. Fuel *properties* are fundamentally intrinsic to a fuel and define the physical processes of combustion, including fuel chemistry, heat content, and density.

FCCS fuelbed inputs

FCCS organizes fuelbed input data into six strata (i.e., canopy, shrubs, nonwoody, woody fuels, litter–lichen–moss, and ground fuels) (see Riccardi et al. 2007). Fuelbed variables used to calculate characteristics of wildland fuels are percent cover (%), height (m), height to live crown (m), live foliar moisture content (%), density (stems·ha^{-1}), diameter at breast height (DBH; cm), diameter (cm), percent live (%), loading (W_n; kg·m^{-2}), depth (cm), width (m), length (m), radius (m), and percent of trees affected (%) (Ottmar et al. 2007). Where appropriate, species designations are required and must be associated with a relative cover (%). In the FCCS user interface, variables are entered in English units, but outputs may be reported in metric units.

FCCS inferred variables

The FCCS inferred variables are internal datasets used in calculations of physical characteristics of wildland fuels. Inferred variables are used in association with a plant species or type designation (e.g., moss type and woody fuel accumulation type). Unlike fuelbed inputs, inferred variables cannot be modified by users. They include fuel properties such as fuel chemistry, heat content, particle density, and bulk density. Many of these data were derived in the development of the fire spread model (Rothermel 1972; Scott and Burgan 2005) or are based on published and unpublished data (Roger Ottmar, 2005, personal communication). The FCCS inferred variables are accessible online at www.fs.fed.us/pnw/fera/fccs/inferred_variables/ and include

(1) BioEqID: equation ID for the allometric shrub biomass equation.
(2) Bulk density (ρ_b; kg·m^{-3}): published bulk density data taken from the Natural Fuels Photo Series (Ottmar et al. 2004) or other sources (Anderson 1969; Pagni and Peterson 1973) and expert opinion (R.D. Ottmar, 2006, personal communication).
(3) Crown shape: a geometrical adjustment factor used to differentiate crown shapes of coniferous trees (0.33) and broadleaf trees (0.50) in volume and loading calculations.
(4) Flammability index (dimensionless): used in the FCCS Fire Potentials. This index allows for the designation of species with special properties with respect to fire. Accelerant species are those that have extractives (e.g., terpenes, fats, waxes, and oils; particularly terpenoid hydrocarbons and lipids) that provide a ready source of combustible volatiles. High heat of combustion, volatility, and lower limits of flammability increase the flammability of accelerant species (Pyne et al. 1996). Neutral species do not contribute to fire behaviour.
(5) Fuel area index (FAI; dimensionless): total fuel surface area per unit ground area (Sandberg et al. 2007*b*). Calculated for most categories and subcategories; inferred by ladder fuel type.

(6) Loading ($kg \cdot m^{-2}$): fuel load. Calculated for most categories and subcategories; inferred by ladder fuel type.
(7) Low fuel heat content (h; $kJ \cdot kg^{-1}$): heat of a material produced by combustion.
(8) Particle density (ρ; $kg \cdot m^{-3}$): taken from standard sources (Wenger 1984; Hoadley 1991); however, when published values are not available, a default value of 400 $kg \cdot m^{-3}$ is used for foliage and sound wood and 300 $kg \cdot m^{-3}$ for rotten wood.
(9) Surface-to-volume ratio ($\bar{\sigma}$; $cm^2 \cdot cm^{-3}$): the ratio of surface area to volume based on data for cylinders (Fons 1946).

Quantification of fuel characteristics

The FCCS quantifies fuel characteristics based on user inputs and inferred variables. Calculations are cumulative, beginning with the lowest hierarchical level (i.e., species or type) and ending at the stratum level (Table 1). Some characteristics by stratum are simply summaries of fuelbed inputs, including percent cover, height or depth, height to live crown, live foliar moisture, and density. Other characteristics are calculated by using algorithms detailed in the following sections.

Fuel area index

Fuel area index ($m^2 \cdot m^{-2}$) is a measure of the total fuel surface area per unit ground area and is analogous to leaf area index (LAI). To assimilate the heterogeneous fuel structures captured by the FCCS fuelbeds, total fuel surface area is calculated for all size-classes of fuels and live foliar biomass. FCCS fire potentials use FAI to calculate the reactive volume of fuels (Sandberg et al. 2007*b*). In each stratum, category, and subcategory, FCCS calculates live fuel FAI, dead fuel FAI, FAI of very fine (flash) fuels (Sandberg et al. 2007*a*; Frandsen 1973), and total FAI. Calculation of FAI is similar for each stratum.

$$[1] \qquad \mathrm{FAI}_{1,2,3} = \Sigma[(W_n\bar{\sigma})/\rho_\mathrm{f}]_i$$

where the subscripts represent an individual stratum (1), category (2), or subcategory (3), summed by species or type i, W_n is the loading by species or type ($kg \cdot m^{-2}$), $\bar{\sigma}$ is the surface area-to-volume ratio inferred by species or type ($cm^2 \cdot cm^{-3}$), and ρ is the particle density inferred by species or type ($kg \cdot m^{-3}$).

Packing ratio

The packing ratio (β) is a measure of fuelbed compactness and is the fraction of the fuel volume that is occupied by fuel. The stratum packing ratio (β_i) is the proportion of the fuelbed stratum (i.e., canopy, shrub, etc.) volume occupied by fuel particles. At very low packing ratios, fire spread is limited and fire intensities are low. At very high packing ratios, lack of oxygen limits fuel combustion. Each fuel environment has an optimum packing ratio for which fuels are ideally configured for maximum fire intensity (Rothermel 1972).

Packing ratio is calculated by species and (or) subcategory in each stratum and summed by stratum.

$$[2] \qquad \beta_{1,2,3} = [\Sigma(W_n/\rho_\mathrm{f})_i]/\delta$$

where δ (depth) is the difference between the base and height of the fuelbed stratum, category or subcategory (m).

Optimum packing ratio (β_op) is calculated for use in FCCS fire potentials (Sandberg et al. 2007*a*, 2007*b*) using the same general equation for every fuel stratum except ground fuels, which are too densely packed to have a theoretical optimum packing ratio,

$$[3] \qquad \beta_\mathrm{op1} = (Y_1\beta_1)/\delta_\mathrm{op1}$$

where the subscript 1 represents an individual stratum, Y_i is the bulk volume of the flammable portion of the fuel stratum ($m^3 \cdot m^{-2}$; this variable includes accelerant tree foliage and rotten snags in the canopy stratum, accelerant foliage in shrub nonwoody fuels strata, sound and rotten woody debris in the woody fuels stratum, and all lichen, litter, and moss), β_1 is the stratum packing ratio, and $\delta_{\mathrm{op}i}$ is the optimum fuelbed depth (m) of a stratum at which fuel particle spacing results in maximum reaction intensity (Sandberg et al. 2007*b*).

Fuel depth

The depth of each fuel stratum and category is a basic measure of the vertical structure of a fuelbed. To be consistent with common usage, the term height (m) is used in canopy, shrub, and nonwoody fuels strata, whereas depth (cm) is used for woody, litter–lichen–moss, and ground fuels strata. The woody fuels stratum contains fuels that are generally continuous (e.g., sound and rotten down woody fuels) and fuels that are by nature discontinuous (e.g., stumps and woody fuel accumulations). FCCS considers only the depth of sound and rotten woody fuels in the woody fuels stratum.

$$[4] \qquad \mathrm{Depth} = \mathrm{Height}_\mathrm{top} - \mathrm{Height}_\mathrm{bottom}$$

where $\mathrm{Height}_\mathrm{top}$ (m) is the top height of a fuel layer and $\mathrm{Height}_\mathrm{bottom}$ (m) is the bottom height of a fuel layer.

Fuel loading

W_n is a fundamental parameter involved in many calculations in FCCS including FAI and packing ratio. Loading calculations are handled differently for each stratum, category, and subcategory.

Canopy stratum loading is the sum of all ladder fuel, tree, and snag loadings. Ladder fuel loadings are inferred by ladder fuel type. Tree loading ($W_{n2,3}$) calculations estimate foliage and small branch biomass of the tree subcategory (i.e., overstory, midstory, and understory) and category and do not include large branches or tree boles.

$$[5a] \qquad \text{Tree loading}\ (W_{n2,3}) = \Sigma[\mathrm{ACV}_4\rho_\mathrm{b4}]$$

$$[5b] \qquad \mathrm{ACV}_4 = \Sigma Y_4 \mathrm{RelCov}_4 CS_4$$

$$[5c] \qquad Y_4 = \mathrm{RelCov}_4\,(\mathrm{Height}_3 - \mathrm{HLC}_3)10\,000\ \mathrm{m}^2\cdot\mathrm{ha}^{-1}$$

where ACV_4 is the adjusted crown volume by tree species (eq. 5*b*; $m^3 \cdot m^{-2}$), Y_j is the canopy bulk volume by tree species (eq. 5*c*; $m^3 \cdot m^{-2}$), RelCov_k is the proportional cover of each tree species, CS_4 is an inferred factor by tree species

Table 1. Calculated fuelbed characteristics generated and output by the Fuel Characteristic Classification System (FCCS).

Variable	Generalized equation	Lowest level calculated	Comment
Loading (W_n)		Species	Equation specific to stratum and (or) category
Live loading		Species	Equation specific to stratum and (or) category
Dead loading		Species	Equation specific to stratum and (or) category
FAI	$\mathrm{FAI} = W_n(\bar{\sigma})/\rho_f$	Species	Uses inferred variables $\bar{\sigma}$ and ρ_f
Percent cover (θ)		Species	Input data
Packing ratio (β)	$\beta = (W_n/\rho_f)/\mathrm{Depth}$	Species	Uses inferred variable ρ_f
Stratum packing ratio (β_i)	$\beta_i = (W_n/\rho_f)/\mathrm{MaxDepth}$	Stratum	MaxDepth is the maximum difference between the base and height of the fuelbed layer
Optimum packing ratio (β_{opt})	$\beta_{op} = [(\mathrm{Volume}/43\,560)\beta_i]/d_{op}$	Stratum	Volume is the bulk volume of fuel; 43 560 is a conversion factor; and d_{op} is optimum fuelbed depth
Density		Subcategory and (or) category	Input data (e.g., trees, stumps, and woody fuel accumulations)
Height to live crown		Tree category	Input data
Height		Subcategory and (or) category	Input data
Depth (δ)	$\mathrm{Height_{Top}} - \mathrm{Height_{Bottom}}$	Subcategory and (or) category	Input data; $\mathrm{Height_{top}}$ and $\mathrm{Height_{bottom}}$ refer to the top and base height of the fuel layer, respectively
Live foliar moisture		Subcategory and (or) category	Input data (e.g., trees, shrub layers, and nonwoody fuel layers)

Note: Most fuelbed characteristics are calculated at the species level and summed to subcategory, category, and stratum levels. W_n, loading; FAI, fuel area index; $\bar{\sigma}$, surface to volume ratio; and ρ_f, foliage particle density.

used to more accurately represent species crown shape in the calculation of volume and loading, and Height_j and HLC_j are height and height to live crown of the tree subcategory, respectively.

Loading for the crown portion of class 1 snags with foliage is calculated as is tree loading (eqs. 5*a*–5*c*) with the following exception: Height_3 is adjusted under the assumption that one third of the snag is foliage and two-thirds is the bole, and percent cover is approximated by the basal area of class 1 snags. Loading calculations of the other snag subcategories are based on standard forest measures

$$[6]\qquad W_{n3} = \Sigma[1/4(\mathrm{Diameter}_3/100)^2\pi\mathrm{Height}_3\mathrm{Density}_3\rho_{r4})\ \mathrm{RelCov}_4]/10\,000\ \mathrm{m}^2\cdot\mathrm{ha}^{-1}$$

where $\mathrm{Diameter}_3$ pertains to the snag subcategory (cm), 100 $\mathrm{cm}\cdot\mathrm{m}^{-1}$ is a conversion factor, Height_3 (m) and $\mathrm{Density}_3$ ($\mathrm{stems}\cdot\mathrm{ha}^{-1}$) are in the snag subcategory, ρ_{r4} (rotten wood particle density) is a mean value based on species, and RelCov_4 is the proportion of each species.

Shrub stratum loading is the sum of shrub species loadings in the primary and secondary shrub layers. Because of a paucity of data available on shrub species loading, allometric equations have been taken or adapted from published and unpublished literature. Shrub species loadings are calculated from allometric equations based on percent cover and occasionally shrub height.

Nonwoody stratum loadings are input variables in FCCS fuelbeds (Table 1). In the absence of actual field data, grass and herb loading are available for many different ecosystems in the Natural Fuels Photo Series (Ottmar et al. 2004).

Woody fuels stratum loadings are divided into two categories: continuous fuels, which include sound and rotten woody loadings by size-classes, and discontinuous fuels, which include stumps and woody fuel accumulations. Sound and rotten fuel loadings are input variables by diameter size-class. Stump loadings by stump subcategory (sound, rotten or lightered–pitchy) are calculated based on input dimensions (Table 1) and are

$$[7]\qquad W_{n3} = \Sigma\left[1/4(\mathrm{Diameter}_3/100)^2\pi\mathrm{Height}_3\mathrm{Density}_3\rho_{w4}\ \mathrm{RelCov}_4\right]/10\,000\ \mathrm{m}^2\cdot\mathrm{ha}^{-1}$$

where $\mathrm{Diameter}_3$ is of the stump subcategory (cm), 100 $\mathrm{cm}\cdot\mathrm{m}^{-1}$ is a conversion factor, Height (m) and Density ($\mathrm{stems}\cdot\mathrm{ha}^{-1}$) are of the stump subcategory, ρ_w (mean wood particle density) is inferred by species, RelCov is the proportion of each species, and 10 000 is a conversion factor from ha to m^2. In the application of ρ_w, sound wood particle densities (ρ_s) by species are used for sound stumps and rotten wood particle densities (ρ_r) are used for rotten and lightered–pitchy stumps.

Woody fuel accumulation loadings are calculated based on input dimensions (Table 1) and equations developed by Hardy (1996). Pile, windrow, and jackpot subcategories are calculated as follows:

$$[8a]\qquad W_{n3} = Y_3\rho_{b3}/10\,000$$

$$[8b]\qquad Y_{\mathrm{Jackpot}},\ Y_{\mathrm{Pile}} = [(\pi\mathrm{Width}_3\mathrm{Height}_3)/8]\mathrm{Density}_3 \quad \text{or Windrow} = [(\pi\mathrm{WidthHeightLength})/4]\mathrm{Density}_3$$

where Y is the volume of woody fuel accumulation type ($\mathrm{m}^3\cdot\mathrm{m}^{-2}$), ρ_b ($\mathrm{kg}\cdot\mathrm{m}^{-3}$) is the bulk density inferred by woody fuel accumulation type, Width_3 (m), Height_3 (m), Length_3, and $\mathrm{Density}_3$ ($\mathrm{no.}\cdot\mathrm{ha}^{-1}$) pertain to the woody fuel accumulation type, π is the ratio of the circumference to the diameter of a circle, and the constant 8 is used for jackpots and piles while 4 is invoked for windrows.

Litter–lichen–moss stratum loading is calculated individually for litter, lichen, and moss type based on inferred bulk densities by type, input depth, and percent cover. They are then summed by category and stratum

$$[9] \qquad W_{n1,2} = \Sigma\rho_{b4}\delta\text{Cover}_2$$

where ρ_b is the bulk density (kg·m^{-3}) by type, δ is the depth (cm) of the category layer (i.e., litter, moss, or type), and Cover_2 is the percent ground cover by area of each category.

Ground fuels stratum loading is the sum of all ground fuel types, including duff (upper and lower layers), squirrel middens, and basal accumulations. Duff is generally considered to be a continuous fuel, whereas squirrel middens and basal accumulations are discontinuous. They therefore may differ in their potential to affect fire spread in a ground fire. Duff loading is the sum of upper and lower duff loadings, which are calculated based on inferred bulk density and input depth (eq. 9). Loadings of squirrel middens and basal accumulations are inferred by FCCS and are based on empirical fuels data (Ottmar and Vihnanek 1998).

After total fuel loadings are calculated, live and dead loadings are based on one of two factors: (1) designation of live or dead by an inferred internal variable or (2) as an input variable (percent live) in the shrub and nonwoody strata.

Case studies: evaluating fuel treatments in dry western forest types of North America

The following case studies show how FCCS can be used to quantify changing fuel characteristics under fuel reduction prescriptions. Four pairs of FCCS fuelbeds were selected for this exercise, each of which represented common fuelbed types in the intermountain West and for which input data are fully referenced.

(1) The western juniper / sagebrush savanna fuelbeds (FCCS 55 and 58) represent pre- and post-prescribed burning in juniper savannas sampled in the John Day Fossil Beds National Monument (USDI National Park Service 2003). Fire exclusion has resulted in juniper encroachment into bordering sagebrush steppe, and the prescribed burn fuelbed (FCCS 58) represents fuel conditions 2 years after a prescribed burn to reduce juniper densities.

(2) The interior ponderosa forest fuelbeds (FCCS 211 and 222) are based on data from Grand Canyon National Park in which dense thickets of ponderosa pine (*Pinus ponderosa* Dougl. P. & C. Laws.) have resulted from fire exclusion (USDI National Park Service 2003). The prescribed burn fuelbed (FCCS 222) represents fuel conditions 2 years after multiple prescribed fires were employed to reduce tree density and woody fuels.

(3) The Gambel oak – bigtooth maple forest fuelbeds (FCCS 216 and 217) are mixed forests with ponderosa pine, other conifers, Gambel oak (*Quercus gambelii* Nutt.), and bigtooth maple (*Acer grandidentatum* Nutt.). Fuelbeds were compiled from data collected in Zion National Park where fire exclusion has caused elevated fuels levels (USDI National Park Service 2003). The prescribed fire fuelbed represents fuel conditions 5 years after a prescribed burn to reduce hazardous fuel loads.

(4) The ponderosa pine – white fir / trembling aspen forest fuelbeds (FCCS 219 and 220) were compiled from montane forests in Grand Canyon National Park (USDI National Park Service 2003). These mixed conifer forests are dominated by white fir (*Abies concolor* (Gord. & Glend.)), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), Englemann spruce (*Picea engelmannii* Parry ex Engelm.), ponderosa pine, and trembling aspen (*Populus tremuloides* Michx.). The prescribed burned fuelbed (FCCS 220) represents fuel conditions 2 years postfire.

In all four case studies, fuel loadings calculated from data entered in each of the FCCS fuelbeds show clear declines in overall surface fuel loads (Fig. 1). The western juniper fuelbeds, being savanna types, contained more nonwoody fuel (i.e., grass) than the other fuelbed pairs. Prescribed burning of the western juniper fuelbeds reduced nonwoody fuels and eliminated woody fuels. The woody fuel stratum dominated the other three forest types, and prescribed burns generally reduced woody fuel loads. Litter decreased substantially in the ponderosa pine / mixed-conifer forest types, but increased somewhat in the Gambel oak dominated mixed forest, possibly because of subsequent mortality incurred by the burn prescription.

Discussion

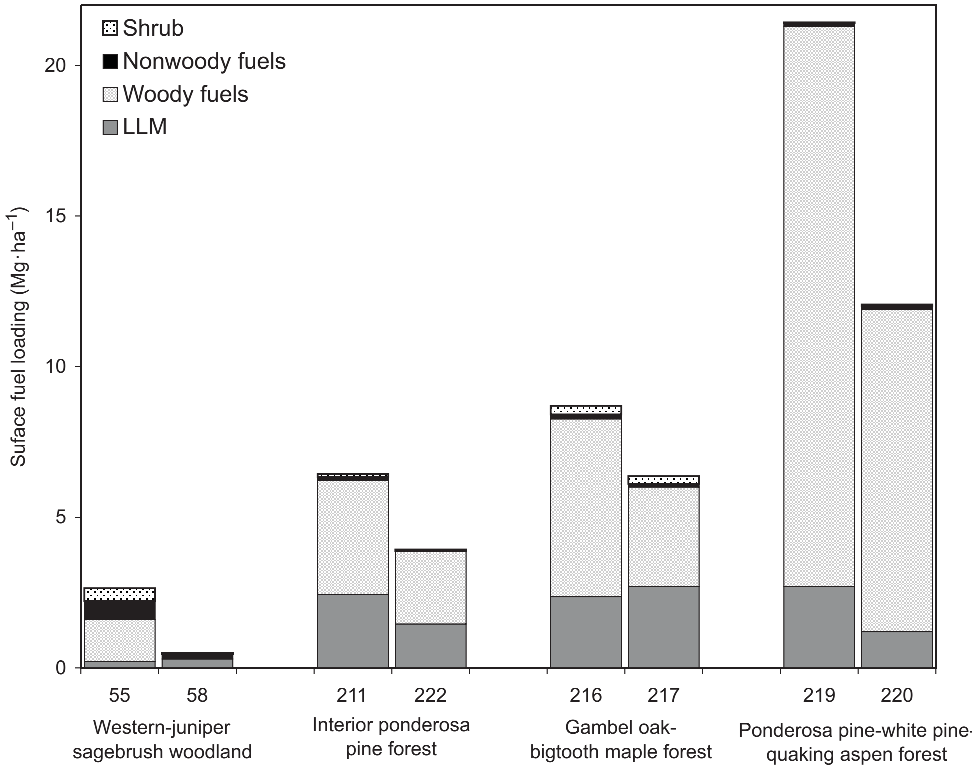
Wildland fuelbeds are complex agglomerations of combustible organic matter. The FCCS provides a tool to create and catalogue fuelbeds that represent realistic characteristics and physical properties of wildland fuels. Fuelbeds are compiled and calculated using the best available data and can be customized for specific applications (Riccardi et al. 2007). The ability of FCCS to catalogue and summarize complex fuelbeds allows calculated results to be used in a variety of applications.

Surface fuelbed data are useful for predicting fire spread and intensity, either directly by using a reformulated Rothermel (1972) fire spread model by Sandberg et al. (2007*b*) or indirectly by crosswalking a fuelbed to a stylized model using BehavePlus (Andrews et al. 2003) or FARSITE (Finney 1998). Surface fuels are usually defined as those contiguous with the surface and less than approximately 2 m tall. Variables that are especially relevant to surface fire behaviour predictions are surface fuel loading, arrangement (percent cover and mean depth or height), fuel morphology, species phenology (i.e., live shrub and nonwoody fuel by species), and ground cover, all of which are characterized and summarized by FCCS.

As described by Schaaf et al. (2007) the initiation and spread of fires in tree canopies is affected by canopy volume (calculated from tree height, crown shape, or tree species) and the mass of flammable species (usually all conifers and a few hardwood species, from crown bulk density or LAI), height to the base of live canopy, percent canopy cover, and at least a qualitative measure of the abundance and type of "ladder fuels" that may provide vertical continuity. These variables can be readily output by FCCS.

Several fuel characteristics that are important in determining fire behaviour are under continual flux. Packing ratio and size of fuel particles, altered by a variety of disturbance and decay processes, regulate combustion processes through their influences on heat transfer and the availability of oxygen to the fuel (Rothermel 1972). Continuity of fuel particles, also subject to a wide variety of disturbance and decay

Fig. 1. Calculated loading values for the shrub, nonwoody fuels, woody fuels, and litter–lichen–moss strata under fire exclusion versus prescribed fire scenarios for four dry forest ecosystems. Example Fuel Characteristic Classification System (FCCS) fuelbeds are 55, western juniper / sagebrush savanna (fire exclusion); 58, western juniper / sagebrush savanna (prescribed fire); 211, interior ponderosa forest (fire exclusion); 222, interior ponderosa forest (prescribed fire); 216, Gambel oak – bigtooth maple forest (fire exclusion); 217, Gambel oak – Bigtooth maple forest (prescribed fire); 219, ponderosa pine – white fir / trembling aspen forest (fire exclusion); and 220, ponderosa pine – white fir / trembling aspen forest (fire exclusion).



processes, affects fire spread. Vertical arrangement of fuel in relation to tree crowns changes as stand structure develops over time and influences fire spread (Davis 1959). In management treatment design, failure to understand and account for temporal and spatial variability in fuel characteristics can result in unexpected consequences (e.g., damage to root systems from prolonged burning of duff or water repellency in soils) (Thomas and Agee 1986; DeBano 2000; Certini 2005). Fuel variability within a unit can often equal or surpass the variability of fuels across the landscape (Harmon et al. 1986).

The FCCS can accommodate the natural variability of fuels because fuelbed data can be modified, thus creating an unlimited number of fuelbeds for specific applications. As illustrated in the four case study fuelbed pairs, FCCS can be used to document changing fuel conditions. In these case studies, FCCS documented declines in surface fuel loadings as a result of prescribed fire and resolved differences in fuel loadings by shrubs, nonwoody fuels, woody fuels, and litter–lichen–moss strata (Fig. 1). FCCS can accommodate much greater fuelbed complexity because it collects input data in categories and subcategories within each stratum (Riccardi et al. 2007).

The FCCS uses fuelbeds as inputs to a reformulated Rothermel (1972) spread model that calculates energy release and one-dimensional spread rate in quasisteady-state fire in heterogeneous but spatially uniform wildland fuels (Sandberg et al. 2007*a*). Mathematical modeling of fire behaviour is an important component of research into understanding of physical properties and characteristics of wildland fuels. However, the increasing need for accurate fuels data in ecological analysis and planning (Fulé et al. 2001; Hardy et al. 2001; Schoennagel et al. 2004) requires quantifiable fuel descriptions with greater detail and documentation. The FCCS is the most comprehensive effort to date to quantify and classify wildland fuel characteristics (see Sandberg et al. 2007*b*, for a review of other fuel classification systems).

Carbon flux can estimated by the abundance and size distribution of all fuel bed categories using FOFEM 5.x (available from www.fire.org/), Consume 3.0 (available from www.fs.fed.us/pnw/fera/research/smoke/consume), or FEPS (available from www.fs.fed.us/pnw/fera/feps/) to predict flaming and smoldering consumption for each fuelbed category based on the diameter or depth of each category. The most critical variables in estimating carbon fluxes are coarse sound and rotten woody debris, woody fuel accumulations, and ground fuels loadings. Of secondary importance is the canopy loading and fine surface fuel loadings. Carbon storage can simply be calculated as approximately one-half of the fuel loadings (Birdsey 1992).

Summary characteristics of fuelbeds available within FCCS will be useful for other applications. For example, data on forest structure and woody debris are critical for determining habitat components for mammal, bird, and amphibian species. Most ecologists are familiar with general vegetation characteristics, and the availability of detailed fuel information provides an opportunity to explore structures and processes of terrestrial ecosystems. Finally, resource managers can now develop long-term plans for fuel and vegetation treatments with much greater resolution over space and time than was previously possible.

Despite the many uses for wildland fuels data, information and research on the basic physical properties and characteristics of fuels is scarce. We anticipate the facilitation of fuels research through use of the nationwide fuel evaluation capability of FCCS. In addition, we anticipate that our approach to calculating fuel characteristics will enable the application of more robust fuels information to various ecological and planning issues. Some aspects of the calculation of physical characteristics of fuels could be improved in future versions of FCCS, especially the inferred variables used in many of the calculations. In addition, we are working to incorporate the ability for users to display fuelbed references and to enter and modify environmental variables. Finally, we will continue to improve our data exporting capabilities so FCCS results may be more easily used in other modeling frameworks.

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