Fuel Consumption Models for Pine Flatwoods Fuel Types in the Southeastern United States

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ABSTRACT

Modeling fire effects, including terrestrial and atmospheric carbon fluxes and pollutant emissions during wildland fires, requires accurate predictions of fuel consumption. Empirical models were developed for predicting fuel consumption from fuel and environmental measurements on a series of operational prescribed fires in pine flatwoods ecosystems in the southeastern United States. Total prefire fuel loading ranged from 4.6 to 23.7 Mg·ha^{-1} (2.1 to 10.6 tons·acre^{-1}); between 12 and 69% of the total loading was composed of shrub species, including saw palmetto (*Serenoa repens*), gallberry (*Ilex glabra*), and other common associates. Fuel consumption ranged from 1.3 to 15.7 Mg·ha^{-1} (0.6 to 7.0 tons·acre^{-1}). On average, 76% of the prefire fuel loading was consumed, although fuel consumption as a percentage of prefire loading was somewhat variable (range: 28–93%). Model predictors include prefire shrub loading and season of burn for shrub fuels ($R^2 = 0.90$); prefire dead and down woody fuel loading and 10-hour fuel moisture for dead and down woody fuels ($R^2 = 0.68$); prefire litter loading and pine litter fuel moisture for pine litter fuels ($R^2 = 0.92$); and prefire aboveground fuel loading and litter fuel moisture for all aboveground fuels ($R^2 = 0.89$). Models specific to season of burning predicted independent consumption measurements within 4.5% (dormant season) and 12.4% (growing season) for flatwoods fires. The models reported here predicted fuel consumption more accurately than the decision support tools First Order Fire Effects Model (FOFEM) and Consume and will allow fire and fuels managers in the region to better estimate fuel consumption and air quality impacts from prescribed burning.

Keywords: fire effects, gallberry, longleaf pine, modeling, saw palmetto, shrubs

Regularly occurring fires are common and represent a natural process for numerous ecosystems in which shrubs are the primary form of combustible biomass, including many forest types with shrub-dominated understories in the southeastern United States. Past policies and management practices have contributed to altered vegetation structure and composition, accumulations of fuel, and changes to historical fire regimes (Tilman et al. 2000, Fellows and Goulden 2008). Prescribed fire is used extensively, particularly in the southeastern United States, to maintain or restore ecosystem properties (Hiers et al. 2007, Keeley et al. 2009), improve wildlife habitat (Wade and Lunsford 1989), encourage specific vegetative and silvicultural changes (Outcalt and Foltz 2004), and control fuels and potential fire behavior (Wade and Lunsford 1989, Brose and Wade 2002).

Despite the many potentially beneficial aspects of fire in ecosystems, pollutant emissions from wildland fires degrade air quality, potentially impairing visibility and negatively affecting human health and safety. The federal Clean Air Act regulates air pollutants, including emissions produced during prescribed fires (Sandberg et al. 2002), so measurements or estimates of emissions from fires are necessary to manage fire-related air quality impacts and to set, and assess compliance with, regulatory standards (Hardy et al. 2001). Large amounts of smoke can be emitted, which may negatively impact air quality, when and where areas with shrub-dominated fuelbeds burn (Hu et al. 2008).

The biomass of the understory shrub component in southern pine forests and, therefore, the amount of fuel available to combust and generate emissions varies with site quality, species composition, and successional status, and can exceed 12 Mg·ha^{-1} (McNab et al. 1978, Ottmar and Vihnanek 2000, Ottmar et al. 2003, Vihnanek et al. 2009). Only a portion of shrub biomass is typically consumed during fires in southern pine forests (Hough 1968, Southern Forest Fire Laboratory Staff 1976), however, so science-based assessments or estimates of fuel consumption and related fire effects are important considerations for effective fuel, fire, air, and land management. Tools for accurately estimating fuel consumption in shrub-dominated vegetation types during prescribed fires are, therefore, critical for modeling terrestrial and atmospheric fire effects (Goodrick et al. 2010).

Prescribed Fire and Southern Pine Forests

In pine forests of the southeastern United States, particularly those dominated by longleaf (*Pinus palustris* Mill.), slash (*P. elliottii* Engelm.), and pond pine (*P. serotina* Michx.), prescribed fire is used to control excessive growth of understory and midstory vegetation to limit the accumulation of fuel, promote ecosystem restoration,

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; millimeters (mm): 1 mm = 0.039 in.; megagrams (Mg): 1 Mg = 2,204.6 lb; hectares (ha): 1 ha = 2.47 ac.

and improve and maintain habitat for fire-adapted plants and animals (Wade and Lunsford 1989, Wade et al. 2000). Maintenance of southern pine forests through regular application of fire limits fuel accumulation, minimizes air quality impacts, and reduces potential severity of wildfires should they occur (Wade and Lunsford 1989, Abrahamson and Hartnett 1990, Brose and Wade 2002, Ottmar and Prichard 2012).

Plant-species diversity and vigor in southern pine forests are promoted by frequent prescribed fire, and several wildlife species, including the federally endangered red-cockaded woodpecker (*Picoides borealis*), benefit from open understory conditions in mature pine forests that are maintained by frequent, low-intensity surface fires (Wade and Lunsford 1989, Robbins and Myers 1992, Wade et al. 2000, Varner et al. 2005, Hiers et al. 2007). Prescribed fire creates mineral seed beds necessary for longleaf, slash, and pond pine regeneration; releases suppressed species with small stature such as shiny blueberry (*Vaccinium myrsinites* Lam.) and dwarf huckleberry (*Gaylussacia dumosa* (Andrews) Torr. & A. Gray) that are otherwise overtopped by unrestrained growth of taller understory species; and promotes flowering of wiregrass (*Aristida stricta* Michx.) and other important herbaceous species (Abrahamson and Hartnett 1990).

In many southern pine forests, particularly those classified as flatwoods, which are the subject of this study, nutrients become sequestered in live vegetation, such as saw palmetto (*Serenoa repens* (W. Bartram) Small) and its associates, and pine needle litter that is relatively slow to decompose (Gholz and Fisher 1982, Hough 1982, Gholz et al. 1985, Abrahamson and Hartnett 1990). Prescribed fire accelerates nutrient turnover, releasing minerals in plant-available forms and stimulating nitrogen fixation by the postfire biota, which may compensate for nitrogen losses through volatilization (Lewis 1974, Wade and Lunsford 1989). Fire-induced effects on nutrient dynamics are thought to positively influence timber productivity over the long-term, although there is conflicting evidence on this topic (Wade and Johansen 1986).

Fuel Consumption and Emissions Research

Emissions of a particular pollutant from a fire are calculated as the product of the area burned, the mass of the fuel consumed per unit area burned, and an emission factor (i.e., the amount of a pollutant emitted for a measured amount of fuel consumed; Seiler and Crutzen 1980). Fuel consumption is the quantity of biomass fully combusted and converted to carbon gases, water vapor, other volatile gases, ash, and airborne particulate matter, and is typically determined by measuring the difference between the prefire and postfire fuel mass or loading. The ability to accurately predict fuel consumption enables resource professionals to plan for and manage smoke from fires and to mitigate negative impacts associated with air pollution (Goodrick et al. 2010).

Most research documenting and modeling fuel consumption has focused on dead and down woody material, leaf and needle litter (i.e., the O_i horizon), and duff (i.e., the O_e and O_a horizons, composed of fermented and decomposed organic material that develops beneath the O_i horizon) in forested ecosystems (see Wright 2010 for a more detailed description of previous research documenting and modeling fuel consumption). Data and models for predicting fuel consumption (and emissions) where shrubs are the primary fuel are limited. With the exception of a small part of the work of Hough (Hough 1968, 1978, Hough and Albini 1978) and Ward (1983) in southern pine forests, little research has documented consumption of forest understory vegetation dominated by shrub fuels. Estimates of fuel consumption and emissions from live shrub fuels are based primarily on expert opinion or rules-of-thumb. For example, in pocosin fuel types in the southern United States, FOFEM v5.9 (Reinhardt 2003, Keane et al. n.d.) predicts 80 or 90% consumption of shrub fuels depending on the season of burning. FOFEM v5.9 also uses models from Hough (1978) that are based on data collected on prescribed fires in slash pine fuel types for all nonpocosin types throughout the southern United States. Similarly, Consume v2.1 (Ottmar et al. n.d.) assumes 70% consumption of all shrub fuels regardless of fuel characteristics, fuel conditions, or fire weather, and Consume v3.0 (Ottmar et al. 2009, Prichard et al. n.d.) uses a preliminary shrub consumption model that is based on data from big sagebrush fires (Wright and Prichard 2006) for all shrub fuels. The *Southern Forestry Smoke Management Guidebook* (Southern Forest Fire Laboratory Staff 1976) does include tables for estimating "available fuel" in southern pine forests, which is assumed here to be equivalent to predicted fuel consumption, under variable fuel loading and fuel moisture conditions. The guidebook, however, does not explicitly document specific models and data sets used to develop the relationships expressed therein.

Inadequate models for predicting or estimating shrub fuel consumption may lead to erroneous emissions estimates. Consumption over-predictions could trigger unnecessary regulatory limitations on the use of prescribed fire in certain settings and circumstances. Likewise, underpredictions could lead to situations in which local and/or regional air quality is compromised, as happened when multiple simultaneous prescribed fires caused a major smoke incursion in the city of Atlanta in February 2007 (Hu et al. 2008). Effective prescribed fire management, therefore, requires accurate estimates of fuel consumption and the resulting fire effects, including emissions.

In this study, I developed empirical models to predict fuel consumption in pine flatwoods forest ecosystems from measurements of shrubs and other fuels before and after fires and day-of-burn environmental conditions. The models developed as part of this study will be programmed into Consume (Ottmar et al. 2009) and its successor programs. Shrub fuel consumption estimates based on field observations will allow for more informed and effective fire planning and fire use for southern pine forests in which the understory is dominated by shrubby vegetation.

Methods

Study Areas

Study sites were located in pine flatwoods forests in northern Florida and southern Georgia and spanned a range of fuel loadings, fuel moistures, and day-of-burn weather conditions typical of operational prescribed burning activities in the southeastern region (Table 1, Figure 1). Data collection targeted a range of fuel and environmental conditions within the pine flatwoods type in an attempt to maximize the breadth of conditions under which model use is appropriate.

Sampling occurred in longleaf, slash, and pond pine forests with a typical understory of predominantly saw palmetto and gallberry (*Ilex glabra* (L.) A. Gray). Sites included various mixtures of other common flatwoods species, including wiregrass, dwarf live oak (*Quercus minima* (Sarg.) Small), and Chapman oak (*Q. chapmanii* Sarg.). Nonindustrial forest managers may apply prescribed fire as often as every year in flatwoods, but more typically areas are burned on a 3- to 4-year cycle (Sackett 1975, Wade and Lunsford 1989). Sites sampled for this study had all been burned within the previous 5 years. Sites were sampled and burned during the dormant and

Table 1. Summary information for pine flatwoods fires. Operational prescribed burns were conducted on the Apalachicola National Forest (A-...), the Greenwood Plantation (BW-...), Eglin Air Force Base (E-...), Pumpkin Hill Preserve State Park (PH-...), and the St. Marks National Wildlife Refuge (SM-...).

Site	Latitude	Longitude	Overstory species[a]	Canopy cover	Understory species[a]	Burn season	Burn date	State
A-214E	N30°23.3′	W84°30.1′	PIPA	60%	SERE, ARST	Dormant	2/17/2005	Florida
A-214NE	N30°23.7′	W84°30.3′	PIPA, PIEL	62%	SERE, ILGL	Dormant	2/17/2005	Florida
A-214W	N30°23.1′	W84°31.3′	PIPA	47%	SERE, ILGL	Dormant	2/17/2005	Florida
A-215N	N30°24.2′	W84°29.9′	PIPA, PIEL	68%	SERE, QUMI	Growing	4/20/2005	Florida
A-215NW	N30°24.2′	W84°30.3′	PIPA, PIEL	70%	SERE, ILGL	Growing	4/20/2005	Florida
A-215S	N30°23.4′	W84°30.1′	PIPA, PIEL	na	SERA, QUMI	Growing	4/20/2005	Florida
A-302C	N30°17.8′	W84°26.4′	PIPA	34%	SERE, ARST, ILGL	Dormant	2/5/2005	Florida
A-302N	N30°18.1′	W84°25.9′	PIPA	46%	SERE, ARST, ILGL	Dormant	2/5/2005	Florida
A-302S	N30°16.4′	W84°26.1′	PIPA	39%	SERE, ARST, ILGL	Dormant	2/5/2005	Florida
A-303E	N30°18.0′	W84°27.4′	PIPA, PIEL	57%	SERE, ILGL, ARST	Dormant	1/31/2005	Florida
A-342N	N30°04.8′	W84°36.1′	PIPA, PIEL	38%	SERE, ILGL	Dormant	2/8/2005	Florida
A-342S	N30°04.6′	W84°36.2′	PIPA, PIEL	41%	SERE, ILGL	Dormant	2/8/2005	Florida
A-343N	N30°04.7′	W84°36.2′	PIPA	36%	SERE, ILGL, ARST	Growing	7/25/2005	Florida
A-343S	N30°04.6′	W84°36.3′	PIPA, PIEL	25%	SERE, ILGL, ARST	Growing	7/25/2005	Florida
BW-204	N30°50.7′	W84°01.0′	PIPA, PIEL	60%	ARST, SERE	Dormant	2/18/2005	Georgia
BW-215	N30°51.8′	W84°02.3′	PIPA	28%	SERE, ARST, ILGL	Dormant	2/4/2005	Georgia
E-502B-1a	N30°27.2′	W86°45.8′	PIPA, PIEL	45%	SERE, ILGL, QUMI	Dormant	2/6/2005	Florida
E-502B-1b	N30°27.2′	W86°45.8′	PIPA, PIEL	42%	SERE, ILGL, QUMI	Dormant	2/6/2005	Florida
E-502B-1c	N30°27.1′	W86°45.8′	PIPA, PIEL	55%	SERE, ILGL, QUMI	Dormant	2/6/2005	Florida
E-502B-2a	N30°27.2′	W86°44.3′	PIPA, PIEL	49%	SERE, ILGL, QUMI	Dormant	2/6/2005	Florida
E-502B-2b	N30°27.2′	W86°44.3′	PIPA, PIEL	46%	SERE, ILGL, QUMI	Dormant	2/6/2005	Florida
E-502B-2c	N30°27.2′	W86°44.4′	PIPA, PIEL	38%	SERE, ILGL, QUMI	Dormant	2/6/2005	Florida
E-807B-3a	N30°29.2′	W86°15.8′	PIPA, PIEL	56%	SERE, ILGL	Dormant	2/17/2004	Florida
E-807B-3b	N30°29.2′	W86°15.9′	PIPA, PIEL	39%	SERE, ILGL	Dormant	2/17/2004	Florida
E-807B-3c	N30°29.2′	W86°15.8′	PIPA, PIEL	55%	SERE, ILGL	Dormant	2/17/2004	Florida
PH-1N	N30°28.5′	W81°29.4′	PISE[b]	0%	SERE, QUCH	Dormant	2/16/2006	Florida
PH-1V	N30°28.4′	W81°29.5′	PISE	22%	ILGL, SERE	Dormant	2/16/2006	Florida
SM-P17A	N30°05.1′	W84°22.3′	PIPA, PIEL	41%	SERE, ILGL, ARST	Dormant	2/16/2005	Florida
SM-P18A	N30°05.1′	W84°22.3′	PIPA, PIEL	7%	SERE, ILGL	Dormant	2/5/2005	Florida
SM-S1A	N30°09.3′	W84°09.1′	PIPA	45%	ILGL, SERE, ARST	Dormant	1/26/2005	Florida
SM-S1H	N30°08.6′	W84°09.5′	PIPA	49%	ILGL, SERE	Growing	5/23/2005	Florida

[a] ARST, *Aristida stricta*; ILGL, *Ilex glabra*; PIEL, *Pinus elliottii*; PIPA, *Pinus palustris*; PISE, *Pinus serotina*; QUCH, *Quercus chapmanii*; QUMI, *Quercus minima*; SERE, *Serenoa repens.*
[b] In close proximity, no trees in plot areas.

Figure 1. Typical pine flatwoods site at the St. Marks National Wildlife Refuge, Florida.

growing seasons under a variety of fire weather and fuel moisture conditions (see Tables 1–3).

Fuel characteristics, fuel moisture content, fire weather, and fuel consumption were measured in situ on operational prescribed fires at 31 sites in 17 burn units. Where more than one location was sampled within a burn unit, sites were selected to represent different fuel and stand characteristics (e.g., understory and overstory vegetation coverage and composition and fuel loading), were typically widely separated (hundreds to thousands of m) and were ignited at different times and under different weather and fuel moisture conditions during burning operations. Therefore, for modeling purposes, each site was considered an independent observation even though some sites were burned during the same fire event.

Data Collection

Fuel Characteristics and Consumption

Fuel mass, or loading, was measured by destructively sampling prefire and postfire plots. *Plots* were systematically arranged at regular intervals along parallel transects within *sites* with uniform fuel and vegetation characteristics (Figure 2). A visual assessment was used to locate sites with uniform fuels and vegetation. Sites contained 6–14 prefire plots and 9–18 postfire plots; in most cases (25 out of 31 sites), sites included at least 9 prefire and 9 postfire plots. Each set of plots was used to characterize average prefire fuel loading and fuel consumption within the 0.3- to 0.5-ha site within prescribed fire management units that ranged in size from tens to hundreds of ha.

Standing vegetation was clipped from within square plots before and after the fire. Saw palmetto (4.0 m^2 plot) and all other vegetation (1.0 m^2 plot nested within the 4.0 m^2 plot) rooted within the plot frame was cut at ground level and separated into categories (grasses, forbs, live and dead woody shrubs, live saw palmetto, dead saw palmetto) in the field. Leaf and needle litter, and dead and down woody fuels were also collected from within the 1.0 m^2 plots; woody fuels were separated into size classes that correspond to time lag fuel classes (1-hour = $<$0.6 cm, 10-hour = 0.6–2.5 cm, 100-hour = 2.5–7.6 cm, and 1,000-hour = $>$7.6 cm in diameter). When too

Table 2. Day-of-burn weather data for prescribed fires in pine flatwoods sites.

Site	Temp	RH	Wind	DSR[a]	KBDI[b]
	°C	%	$km{\cdot}hr^{-1}$		
A-214E	17.2	51	5.6	3.5	223
A-214NE	15.6	53	6.1	3.5	223
A-214W	17.2	51	5.6	3.5	223
A-215N	22.2	65	1.4	13.0	189
A-215NW	22.8	65	1.4	13.0	189
A-215S	27.8	39	3.5	13.0	189
A-302C	23.1	72	5.0	2.0	149
A-302N	23.1	72	4.3	2.0	149
A-302S	22.7	73	4.3	2.0	149
A-303E	12.2	64	2.4	2.0	180
A-342N	24.4	48	4.0	5.5	162
A-342S	21.7	56	4.8	5.5	162
A-343N	35.0	49	2.4	3.0	201
A-343S	35.0	49	2.4	3.0	201
BW-204	16.1	23	4.0	4.0	234
BW-215	13.9	50	4.8	1.0	31
E-502B-1a	15.0	52	3.2	3.5	20
E-502B-1b	16.7	45	3.2	3.5	20
E-502B-1c	16.7	45	3.2	3.5	20
E-502B-2a	17.8	56	6.4	3.5	20
E-502B-2b	17.8	56	6.4	3.5	20
E-502B-2c	17.8	56	6.4	3.5	20
E-807B-3a	17.2	55	2.4	2.5	92
E-807B-3b	14.4	34	4.0	2.5	92
E-807B-3c	17.2	31	4.8	2.5	92
PH-1N	22.8	68	4.8	12.0	70
PH-1V	21.1	71	4.8	12.0	70
SM-P17A	26.1	53	4.8	2.5	198
SM-P18A	15.6	44	3.2	2.5	122
SM-S1A	25.3	46	2.9	3.5	116
SM-S1H	29.7	51	15.3	2.5	311

[a] DSR, Days since > 6 mm of measured rainfall at the nearest Remote Automated Weather Station.
[b] KBDI, Keetch-Byram Drought Index; lower numbers indicate wetter conditions.

abundant or large to collect (3 out of 31 sites), woody material > 2.5 cm in diameter was measured on two 76.2-m-long planar intersect transects (Brown 1974). All clipped and collected material was returned to the laboratory, oven-dried to a constant weight (100° C for a minimum of 48 hours), and weighed with a precision balance to the nearest 0.1 grams.

Understory vegetation coverage was used as an indicator of horizontal fuel continuity. Coverage by lifeform category (grass, forb, and shrub) was estimated by using the line intercept method (Canfield 1941) along two (and sometimes three) 76.2-m-long transects per site (Figure 2). The entire site burned for most fires; however, in the rare cases where fire spread was patchy, the proportion of the area burned was assessed by measuring the amount of blackened ground that was intercepted by transects that were parallel and offset 3 m from the original vegetation coverage transects. Canopy coverage was measured with a concave spherical densiometer at the end and center points of each vegetation coverage transect to provide a simple indicator of stand structure. Systematically located measurements of grass, forb, woody shrub, and saw palmetto height were made to assess vertical fuel structure.

Fuel consumption was estimated by taking the difference between mean prefire and postfire loading by category of all of the plots at a site. Total fuel consumption was calculated as the sum of the measured fuel consumption for each category.

Fuel Moisture and Fire Weather

Multiple samples each ($n = 5$–10) of grass, live woody shrub leaves, live woody shrub stems, live saw palmetto fronds, live saw palmetto rachis, dead palmetto leaves and rachis (combined), 0.6–2.5 cm in diameter (i.e., 10-hour) dead and down woody material, and pine needle litter were collected from the general plot area in tared, heavy-gauge, sealable plastic bags shortly before ignition of each site to document fuel moisture content. Fuel moisture samples were collected with the intent of testing whether moisture content was correlated with fuel consumption, especially for live fuels, which often do not fully consume during fires. Fuel moisture samples were weighed within 8 hours of being collected, oven-dried at 100° C for at least 48 hours, and reweighed to determine gravimetric moisture content. A single set of fuel moisture samples were used to represent multiple sites in a unit if safety or logistical constraints prevented collection of samples from individual sites (4 out of 17 units).

Temperature, relative humidity, and wind speed were monitored before and during burning with a sling psychrometer or a handheld electronic weather station. The reported values represent weather conditions at the time the plot areas ignited. If temperature and relative humidity measurements made with the sling psychrometer and electronic weather stations differed, psychrometer-measured values were chosen for consideration in model development. Flame length, rate of spread, and whether a fire burned through the site as a backing, heading, or flanking fire were estimated visually by using plot markers with known spacing and height for reference where safety allowed.

Ignition

Plots were burned during the course of operational firing activities and were either ignited by hand on the ground with drip torches or from a helicopter with delayed aerial ignition devices deployed with a plastic sphere dispenser. Plot areas burned with a mixture of fire types but typically burned predominantly as heading or flanking fires from these ignition methods.

Data Analysis

Models to predict fuel consumption in pine flatwoods fuel types were developed from measured fuel and environmental variables by using ordinary least squares (OLS) regression. Candidate predictor variables were selected by examining scatter plots of response and predictor variables and conducting Pearson product moment correlation analyses. Transformations (natural log, square root, and arcsine-square root) of the response and predictor variables were evaluated and used if they linearized relationships and improved a model's adherence to the assumptions of OLS regression. Model development began with the most strongly correlated raw or transformed response and predictor variable. Additional predictors were added to the models by using a manual forward selection process in which the variable with the lowest partial regression coefficient *P*-value was considered for inclusion. Multicollinearity was avoided by assessing the strength of correlation among potential predictors and eliminating highly correlated variables. Adding predictors reduces statistical degrees of freedom, so final models weigh parsimony (two predictors) with variance explanation (maximized R^2). In light of the modest size of the model data set all data were used for model development. Performance was assessed by comparing modeled consumption predictions to independent measurements of consumption (R.D. Ottmar unpublished data, J.B. Cronan unpublished data). Prefire values from the aforementioned independent fuel consumption data sets were also used as inputs for FOFEM v5.9 and Consume v3.0 to compare the performance of existing modeling systems with the models developed here.

Table 3. Day-of-burn fuel moisture data for prescribed fires in pine flatwoods sites.

Site	Grass	Live shrub stem	Live shrub foliage	Live saw palmetto	Pine litter	Dead 10-hour
	% (SD)					
A-214E	42.5 (2.9)	94.2 (6.4)	98.2 (5.4)	112.9 (2.1)	31.8 (2.8)	40.7 (8.6)
A-214NE	50.8 (5.5)	89.8 (5.6)	110.2 (6.4)	119.5 (5.1)	27.0 (3.9)	52.3 (16.7)
A-214W	46.7 (6.0)	92.0 (6.1)	104.2 (8.4)	116.2 (5.1)	29.4 (4.1)	46.5 (13.9)
A-215N	49.6 (12.7)	95.0 (7.9)	113.3 (7.9)	109.0 (5.2)	25.2 (7.6)	16.0 (4.0)
A-215NW	56.0 (17.0)	101.8 (1.3)	116.6 (5.8)	110.8 (4.7)	31.7 (4.8)	18.3 (4.4)
A-215S	44.5 (5.6)	88.1 (4.5)	110.0 (9.1)	107.2 (5.7)	18.8 (1.1)	13.7 (1.7)
A-302C	46.5 (4.8)	91.0 (3.6)	123.1 (4.9)	108.2 (6.3)	38.8 (9.0)	83.5 (10.6)
A-302N	31.6 (7.6)	85.5 (15.0)	118.1 (4.0)	104.6 (18.5)	22.7 (2.0)	74.1 (8.3)
A-302S	61.8 (6.3)	91.6 (2.7)	120.6 (5.0)	126.4 (12.6)	30.8 (10.5)	75.6 (11.7)
A-303E	44.2 (5.0)	86.4 (5.4)	121.0 (4.5)	114.1 (9.0)	35.2 (2.9)	69.2 (13.8)
A-342N	38.4 (2.1)	81.0 (2.4)	118.7 (3.7)	101.8 (3.6)	21.2 (0.7)	46.0 (16.8)
A-342S	45.2 (7.8)	87.6 (3.0)	111.5 (5.4)	113.2 (9.1)	24.9 (1.8)	43.2 (9.0)
A-343N	113.2 (1.3)	123.5 (3.1)	162.9 (6.6)	146.0 (1.9)	10[a]	12[a]
A-343S	113.2 (1.3)	123.5 (3.1)	162.9 (6.6)	146.0 (1.9)	10[a]	12[a]
BW-204	37.6 (6.8)	89.3 (7.0)	115.2 (5.7)	106.2 (4.3)	13.7 (0.6)	25.0 (5.6)
BW-215	39.6 (4.5)	113.5 (6.0)	129.2 (6.6)	114.9 (4.5)	45.0 (12.0)	62.5 (12.1)
E-502B-1a	37.0 (8.1)	73.9 (3.3)	97.6 (7.5)	100.3 (12.3)	36.8 (3.4)	55.0 (11.7)
E-502B-1b	37.0 (8.1)	73.9 (3.3)	97.6 (7.5)	100.3 (12.3)	36.8 (3.4)	55.0 (11.7)
E-502B-1c	37.0 (8.1)	73.9 (3.3)	97.6 (7.5)	100.3 (12.3)	36.8 (3.4)	55.0 (11.7)
E-502B-2a	35.4 (7.9)	71.6 (7.4)	103.8 (3.2)	102.8 (3.1)	23.0 (3.4)	53.7 (12.9)
E-502B-2b	35.4 (7.9)	71.6 (7.4)	103.8 (3.2)	102.8 (3.1)	23.0 (3.4)	53.7 (12.9)
E-502B-2c	35.4 (7.9)	71.6 (7.4)	103.8 (3.2)	102.8 (3.1)	23.0 (3.4)	53.7 (12.9)
E-807B-3a	42.1 (14.8)	75.9 (5.2)	130.6 (3.8)	116.9 (7.5)	48.8 (7.4)	62.2 (10.7)
E-807B-3b	42.1 (14.8)	83.6 (6.1)	130.6 (3.8)	116.9 (7.5)	48.8 (7.4)	62.2 (10.7)
E-807B-3c	42.1 (6.6)	79.4 (6.0)	130.6 (1.7)	116.9 (3.4)	48.8 (2.3)	62.2 (4.8)
PH-1N	24.9 (3.9)	62.2 (2.3)	110.5[b]	111.7 (1.2)	13.3 (3.7)	15.9 (3.9)
PH-1V	24.9 (3.9)	101.0 (2.9)	99.0 (3.2)	121.0 (10.2)	19.2 (3.6)	15.9 (3.9)
SM-P17A	37.8 (5.2)	92.9 (6.2)	102.2 (5.0)	109.4 (3.2)	23.5 (3.4)	53.9 (13.2)
SM-P18A	41.9 (8.8)	89.9 (3.1)	100.5 (7.1)	114.6 (8.5)	33.9 (4.8)	71.2 (15.0)
SM-S1A	63.9 (11.9)	87.9 (2.5)	128.0 (2.3)	106.2 (9.5)	37.6 (6.9)	53.5 (12.2)
SM-S1H	214.5 (61.2)	104.0 (6.0)	150.0 (6.5)	132.4 (5.1)	19.0 (2.7)	20.0 (6.2)

[a] Measured by Apalachicola National Forest personnel, no SD provided.
[b] Only one sample collected.

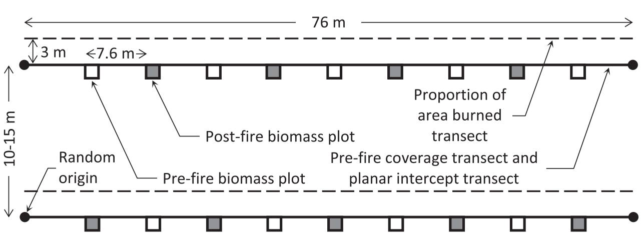

Figure 2. Sampling layout and specifications for pine flatwoods consumption sampling sites. Plots were established at 7.6-m intervals along parallel transects that were oriented on a random azimuth that originated from a random origin point. Saw palmetto, gallberry, shrubby oaks, other shrubs, grasses, forbs, litter, and dead and downed woody biomass were measured on 6–14 plots prefire and on 9–18 plots postfire; the most common layout sampled 9 plots for both prefire and postfire fuel loading. Biomass plots were 4.0 m² for saw palmetto and 1.0 m² for all other fuel categories. Saw palmetto and other shrubs were separated into live and dead fractions during prefire sampling. Palmetto, shrub, forb, and grass coverages were quantified on two (and sometimes three) parallel prefire transects spaced 10–15 m apart. The proportion of the area burned was measured on two postfire transects that were parallel and offset 3 m from the prefire vegetation coverage transects. Prefire saw palmetto, shrub, forb, and grass heights were measured every 3.3–7.6 m along each transect.

The assumptions required of OLS regression analysis (i.e., linear relationship among variables and homogeneous residual variance) were evaluated by examining plots of the standardized residuals, quantiles of the normal distribution, and Cook's distance (Neter et al. 1990, Gotelli and Ellison 2004). One outlier (BW-215), a site with standardized residuals greater than two standard deviations from the fitted value that exerted strong leverage (i.e., Cook's D > 0.4) was removed during data analysis for all models to reduce its effect on model form and to homogenize residual variance. One additional site that was a statistical outlier based on the same criteria (SM-S1H) was also removed from the data set used to model shrub fuel consumption. Statistical analysis was performed with the base package of R (R Development Core Team 2010).

Results

Prefire Fuel Characteristics

Total prefire fuel loading ranged from 4.6 to 23.7 Mg·ha^{-1} (Table 4). Shrub biomass, including various species of woody-stemmed shrubs and saw palmetto, was on average only 32.9% of total biomass. Shrub coverage ranged from 24.4 to 100%, and vegetation stature averaged 0.3–1.2 m as measured by shrub and saw palmetto height, although many plants were taller than the average height (Table 5). The prefire herbaceous component ranged from <0.1 to 3.7 Mg·ha^{-1} and 0.6 to 62.6% coverage (Tables 4 and 5). Litter loading was half of total loading on average, and ≤ 7.6 cm diameter woody surface fuels ranged from 0.2 to 3.1 Mg·ha^{-1} (Table 4).

Fuel Consumption

Both the absolute amount of fuel consumed and the proportion of the prefire loading that was consumed varied across sites (Table 6). Shrub consumption ranged from 0.2 to 6.3 Mg·ha^{-1}, and total biomass consumption ranged from 1.3 to 15.7 Mg·ha^{-1}. Area

Table 4. Prefire fuel loading for pine flatwoods sites.

Site	Herbaceous vegetation		Live saw palmetto		Dead saw palmetto		Woody shrubs		Pine litter		Dead wood		All fuels	
	$Mg \cdot ha^{-1}$ (SD)													
A-214E	0.29	(0.29)	0.45	(0.59)	0.19	(0.27)	2.17	(0.64)	3.38	(1.61)	0.53	(0.60)	7.02	1.26
A-214NE	0.15	(0.18)	1.14	(1.02)	0.46	(0.34)	1.15	(0.73)	6.62	(1.58)	1.19	(0.81)	10.71	2.31
A-214W	0.07	(0.08)	1.22	(0.89)	0.41	(0.35)	1.38	(0.68)	6.91	(2.61)	1.09	(1.09)	11.08	2.65
A-215N	0.54	(0.54)	0.29	(0.41)	0.12	(0.20)	2.36	(1.31)	3.12	(1.27)	0.61	(0.23)	7.03	1.60
A-215NW	0.02	(0.07)	1.08	(1.08)	0.97	(1.15)	1.48	(1.17)	6.83	(3.03)	1.69	(1.20)	12.07	2.91
A-215S	0.55	(0.79)	0.60	(0.67)	0.16	(0.18)	2.19	(1.03)	3.11	(0.95)	0.69	(0.56)	7.30	1.98
A-302C	1.00	(0.83)	0.97	(0.42)	0.86	(0.29)	1.32	(0.69)	4.45	(1.09)	1.00	(0.62)	9.60	2.43
A-302N	0.95	(0.72)	0.70	(0.59)	0.51	(0.37)	1.61	(0.80)	4.87	(1.47)	0.54	(0.51)	9.17	1.87
A-302S	0.37	(0.36)	0.77	(0.59)	0.50	(0.37)	2.05	(1.82)	3.96	(0.81)	0.55	(0.47)	8.20	1.93
A-303E	3.71	(2.14)	0.74	(0.65)	0.86	(0.89)	1.02	(0.55)	3.48	(1.97)	1.02	(0.94)	10.84	3.13
A-342N	0.20	(0.23)	0.49	(0.41)	0.38	(0.32)	1.91	(0.52)	3.43	(1.51)	0.25	(0.27)	6.66	1.43
A-342S	0.39	(0.23)	1.48	(1.63)	1.05	(1.01)	1.83	(1.24)	4.53	(1.37)	0.75	(0.72)	10.03	2.54
A-343N	0.58	(0.31)	0.39	(0.24)	0.35	(0.17)	1.61	(0.41)	1.95	(0.36)	0.53	(0.60)	5.41	1.07
A-343S	0.62	(0.71)	0.54	(0.48)	0.52	(0.49)	2.35	(0.31)	2.54	(1.04)	0.35	(0.36)	6.91	1.23
BW-204	0.90	(0.91)	0.15	(0.31)	<0.01	(0.01)	1.51	(0.79)	5.23	(1.74)	0.44	(0.44)	8.23	2.15
BW-215	1.05	(0.64)	0.18	(0.27)	0.03	(0.05)	0.89	(0.37)	2.07	(2.07)	0.34	(0.28)	4.55	1.30
E-502B-1a	0.25	(0.49)	0.37	(0.58)	0.27	(0.56)	1.82	(0.85)	8.83	(1.91)	2.57	(3.16)	14.11	5.03
E-502B-1b	0.34	(0.31)	0.34	(0.37)	0.25	(0.23)	1.57	(0.37)	6.72	(3.84)	1.75	(1.42)	10.97	3.57
E-502B-1c	0.26	(0.32)	0.66	(0.36)	0.50	(0.20)	1.69	(0.78)	13.21	(4.07)	1.97	(1.73)	18.29	4.82
E-502B-2a	1.36	(1.88)	0.41	(0.73)	0.36	(0.62)	1.24	(0.46)	12.00	(4.85)	1.79	(1.68)	17.16	5.14
E-502B-2b	1.24	(1.54)	0.15	(0.36)	0.09	(0.16)	1.93	(1.62)	8.98	(5.26)	1.87	(2.97)	14.28	7.78
E-502B-2c	1.80	(1.99)	0.38	(0.37)	0.24	(0.22)	1.96	(2.60)	9.61	(3.75)	0.91	(1.59)	14.91	4.71
E-807B-3a	0.15	(0.46)	0.68	(0.73)	0.61	(0.91)	6.44	(10.69)	12.30	(3.53)	3.49	(2.32)	23.67	9.49
E-807B-3b	0.56	(0.98)	0.63	(0.97)	0.41	(0.60)	1.94	(1.48)	10.93	(4.65)	3.17	(2.09)	17.64	5.60
E-807B-3c	0.08	(0.24)	1.31	(1.39)	1.07	(1.17)	2.63	(1.95)	10.11	(2.74)	5.02	(2.59)	20.22	5.13
PH-1N	0.40	(0.48)	0.90	(1.19)	0.87	(1.12)	5.12	(4.48)	2.41	(1.26)	0.31	(0.33)	10.01	5.67
PH-1V	0.28	(0.34)	2.17	(1.99)	1.36	(1.91)	6.38	(3.78)	3.81	(1.85)	1.06	(0.98)	15.06	4.90
SM-P17A	0.65	(1.21)	0.46	(0.50)	0.12	(0.21)	2.42	(0.35)	3.34	(1.32)	0.94	(1.32)	7.94	2.94
SM-P18A	1.04	(0.75)	0.36	(0.32)	0.05	(0.04)	2.47	(0.42)	2.20	(0.95)	0.86	(0.28)	6.99	1.78
SM-S1A	0.75	(1.69)	0.45	(0.54)	0.15	(0.17)	4.92	(3.78)	4.60	(1.35)	1.05	(0.88)	11.92	3.08
SM-S1H	0.77	(0.95)	1.42	(0.99)	0.23	(0.23)	2.60	(1.46)	5.77	(1.11)	0.86	(0.52)	11.66	3.15

Table 5. Prefire coverage, proportion of area burned, and vegetation height for pine flatwoods sites.

Burn unit	Prefire coverage and area burned						Height					
	Grass	Forb	Shrub	Saw palmetto	All veg.	Area burned	Grass		Woody shrub		Saw palmetto	
	%						m (SD)					
A-214E	7.7	0.6	70.7	29.9	100.0	97.0	0.36	(0.12)	0.39	(0.22)	0.73	(0.18)
A-214NE	6.9	0.0	27.7	36.9	71.5	100.0	0.33	(0.12)	0.53	(0.31)	1.00	(0.14)
A-214W	2.6	0.0	44.5	35.5	82.6	100.0	0.27	(0.12)	0.66	(0.31)	1.07	(0.22)
A-215N	9.0	0.0	55.1	14.3	78.4	100.0	0.40	(0.13)	0.42	(0.16)	0.78	(0.15)
A-215NW	1.2	0.0	42.2	20.9	64.3	99.4	0.25	(0.13)	0.56	(0.30)	0.97	(0.19)
A-215S	6.2	0.0	50.5	20.5	77.2	100.0	0.36	(0.11)	0.41	(0.13)	0.85	(0.18)
A-302C	35.5	1.5	46.0	35.2	100.0	100.0	0.51	(0.20)	0.54	(0.26)	0.84	(0.14)
A-302N	62.6	0.0	41.7	28.7	100.0	100.0	0.40	(0.13)	0.39	(0.19)	0.64	(0.14)
A-302S	13.1	0.0	46.3	33.3	92.7	99.6	0.37	(0.12)	0.49	(0.28)	0.70	(0.14)
A-303E	37.5	1.5	28.9	18.9	86.8	98.5	0.61	(0.14)	0.55	(0.24)	0.96	(0.15)
A-342N	11.9	0.0	50.6	29.8	92.3	100.0	0.39	(0.12)	0.55	(0.31)	0.80	(0.12)
A-342S	14.4	0.0	43.0	35.6	93.0	100.0	0.47	(0.12)	0.55	(0.22)	0.84	(0.17)
A-343N	12.4	0.0	45.2	26.2	83.8	99.1	0.34	(0.10)	0.35	(0.16)	0.73	(0.12)
A-343S	21.1	0.0	38.2	37.1	96.4	91.0	0.35	(0.14)	0.48	(0.21)	0.89	(0.12)
BW-204	24.2	0.0	25.3	5.6	55.1	100.0	0.47	(0.07)	0.58	(0.22)	0.70	(0.11)
BW-215	19.1	0.0	28.0	4.0	51.1	33.8	0.32	(0.12)	0.46	(0.19)	0.68	(0.12)
E-502B-1a	35.3	0.0	37.1	12.8	85.2	100.0	0.22	(0.10)	0.55	(0.20)	0.80	(0.15)
E-502B-1b	10.0	0.0	47.4	26.0	83.4	99.3	0.21	(0.09)	0.28	(0.15)	0.53	(0.16)
E-502B-1c	7.9	0.0	33.8	30.7	72.4	100.0	0.21	(0.11)	0.37	(0.15)	0.65	(0.21)
E-502B-2a	57.2	5.3	37.7	16.5	100.0	100.0	0.38	(0.15)	0.58	(0.22)	0.76	(0.17)
E-502B-2b	28.9	1.1	36.0	16.8	82.8	100.0	0.47	(0.21)	0.67	(0.35)	0.82	(0.25)
E-502B-2c	26.2	1.8	15.8	8.6	52.4	100.0	0.32	(0.12)	0.47	(0.21)	0.54	(0.20)
E-807B-3a	1.2	1.5	68.7	28.4	99.8	86.4	0.25	(0.06)	1.15	(0.76)	1.04	(0.17)
E-807B-3b	5.8	0.0	43.4	16.2	65.4	94.5	0.46	(0.11)	0.95	(0.43)	0.81	(0.26)
E-807B-3c	0.6	0.0	29.9	21.6	52.1	87.6	0.16	(0.08)	0.86	(0.48)	0.99	(0.20)
PH-1N	8.8	0.0	59.1	31.8	99.7	97.5	0.32	(0.12)	0.67	(0.33)	0.60	(0.14)
PH-1V	1.4	0.0	45.4	48.4	95.2	100.0	0.23	(0.15)	0.87	(0.28)	0.85	(0.24)
SM-P17A	13.7	0.0	47.0	14.3	75.0	99.2	0.26	(0.10)	0.29	(0.19)	0.55	(0.11)
SM-P18A	18.9	0.0	49.3	27.7	95.9	91.0	0.45	(0.10)	0.52	(0.07)	0.76	(0.05)
SM-S1A	14.9	0.0	63.2	26.2	100.0	98.0	0.39	(0.19)	1.09	(0.50)	1.00	(0.30)
SM-S1H	11.0	0.0	38.8	32.9	82.7	100.0	0.43	(0.17)	0.86	(0.46)	1.03	(0.20)

Table 6. Fuel consumption for prescribed fires in pine flatwoods sites.

Site	Herbaceous vegetation		Saw palmetto		Woody shrubs		Pine litter		Dead wood		All fuels	
	$Mg{\cdot}ha^{-1}$ (SD)											
A-214E	0.29	(0.29)	0.24	(1.20)	1.65	(0.87)	3.04	(1.64)	0.22	(0.71)	5.44	(1.48)
A-214NE	0.15[a]		1.21	(1.34)	0.72	(0.81)	4.73	(2.03)	0.18	(0.98)	6.99	(2.89)
A-214W	0.07	(0.08)	1.17	(1.28)	0.83	(1.14)	5.22	(2.77)	0.03	(1.31)	7.32	(3.05)
A-215N	0.54	(0.54)	0.12	(0.65)	2.08	(1.33)	1.84	(1.86)	0.35	(0.23)	4.92	(2.10)
A-215NW	0.02[a]		1.78	(2.21)	0.77	(1.36)	5.61	(3.21)	0.86	(1.37)	9.04	(3.35)
A-215S	0.55	(0.79)	0.66	(0.83)	2.06	(1.04)	2.73	(1.02)	0.25	(0.67)	6.25	(2.07)
A-302C	0.98	(0.83)	1.59	(0.69)	0.91	(0.89)	4.29	(1.12)	0.48	(0.82)	8.26	(2.60)
A-302N	0.95[a]		1.11	(0.91)	1.40	(0.88)	4.87[a]		0.13	(0.70)	8.46	(1.96)
A-302S	0.37[a]		1.09	(0.95)	1.44	(2.01)	3.65	(0.91)	0.02	(0.66)	6.57	(2.23)
A-303E	3.61	(2.15)	1.44	(1.52)	0.70	(0.65)	2.30	(2.04)	0.45	(1.07)	8.49	(3.23)
A-342N	0.20[a]		0.68	(0.74)	1.32	(0.67)	3.43[a]		0.02	(0.39)	5.66	(1.51)
A-342S	0.39[a]		2.36	(2.64)	1.68	(1.25)	4.53[a]		0.41	(0.81)	9.37	(2.58)
A-343N	0.58[a]		0.60	(0.42)	1.46	(0.43)	1.95[a]		0.01	(0.85)	4.60	(1.25)
A-343S	0.62[a]		0.63	(1.03)	1.76	(0.47)	2.54[a]		0.25	(0.37)	5.81	(1.36)
BW-204	0.89	(0.91)	0.12	(0.32)	1.30	(0.81)	4.12	(1.81)	0.19	(0.46)	6.62	(2.24)
BW-215	0.69	(0.73)	0.03	(0.42)	0.15	(0.64)	0.39	(2.30)	0.00	(0.40)	1.27	(1.98)
E-502B-1a	0.25[a]		0.53	(1.15)	1.22	(0.91)	7.97	(2.28)	1.63	(3.88)	11.60	(5.61)
E-502B-1b	0.34[a]		0.45	(0.61)	1.21	(0.48)	5.43	(4.25)	0.41	(2.18)	7.84	(4.37)
E-502B-1c	0.26[a]		0.98	(0.60)	1.23	(0.83)	11.39	(4.36)	0.29	(3.45)	14.14	(5.87)
E-502B-2a	1.31	(1.89)	0.72	(1.36)	1.00	(0.60)	11.70	(4.97)	1.00	(1.88)	15.73	(5.26)
E-502B-2b	1.24[a]		0.11	(0.56)	1.45	(1.72)	7.59	(5.50)	0.77	(3.23)	11.17	(8.18)
E-502B-2c	1.80[a]		0.47	(0.59)	1.48	(2.64)	9.19	(3.94)	0.10	(1.95)	13.06	(5.00)
E-807B-3a	0.15[a]		0.78	(1.73)	5.18	(10.76)	7.28	(4.67)	1.09	(2.53)	14.48	(10.43)
E-807B-3b	0.56[a]		0.86	(1.59)	0.68	(1.76)	6.57	(4.85)	1.27	(2.51)	9.95	(6.06)
E-807B-3c	0.08[a]		1.94	(2.58)	1.49	(2.24)	7.14	(3.21)	1.86	(3.10)	12.50	(5.92)
PH-1N	0.40[a]		1.56	(2.31)	3.30	(4.86)	2.21	(1.28)	0.30	(0.33)	7.77	(6.01)
PH-1V	0.28[a]		1.67	(4.01)	4.64	(4.00)	3.67	(1.88)	0.71	(1.16)	10.97	(5.64)
SM-P17A	0.65	(1.21)	0.37	(0.75)	1.94	(0.49)	2.65	(1.38)	0.38	(1.41)	6.00	(3.13)
SM-P18A	1.04[a]		0.13	(0.29)	2.13	(0.46)	2.06	(0.97)	0.23	(0.55)	5.60	(1.89)
SM-S1A	0.74	(1.69)	0.17	(0.80)	3.31	(3.87)	4.06	(1.44)	0.29	(0.98)	8.57	(3.32)
SM-S1H	0.76	(0.95)	0.75	(1.47)	0.90	(2.64)	5.39	(1.16)	0.21	(0.98)	8.00	(3.81)

[a] Total consumption of prefire loading.

Table 7. Equations for predicting shrub, nonshrub vegetation, dead and down woody material, litter, and all aboveground biomass consumption for flatwoods prescribed fires.

Equations[a]	n	F-ratio	RSE[b]	Adj. R^2
$\ln C_s = -0.1889 + 0.9049(\ln L_s) + 0.0676(Season)$	29	130.8	0.12	0.90
If $B \geq 0.85$, $C_n = 0.9944(L_n)$	na	na	na	na
If $B < 0.85$, $C_n = 0.9944(L_n) \times B$	na	na	na	na
$\sqrt{C_w} = -0.0108 + 0.7017(\sqrt{L_w}) - 0.0026(F_{10})$	30	31.3	0.18	0.68
$\sqrt{C_l} = 0.2871 + 0.9140(\sqrt{L_l}) - 0.0101(F_l)$	30	176.4	0.16	0.92
$\ln C_a = 0.2664 + 0.9115(\ln L_a) - 0.0988(\ln F_l)$	30	119.1	0.11	0.89

[a] Symbols:
B = area burned, proportion of total area;
C_a = consumption of all aboveground biomass, $Mg{\cdot}ha^{-1}$;
C_l = consumption of litter biomass, $Mg{\cdot}ha^{-1}$;
C_n = consumption of nonshrub vegetation (grasses and forbs), $Mg{\cdot}ha^{-1}$;
C_s = consumption of shrubs (including saw palmetto), $Mg{\cdot}ha^{-1}$;
C_w = consumption of dead and down woody biomass, $Mg{\cdot}ha^{-1}$;
F_{10} = day-of-burn 10-hour fuel moisture, percentage by dry weight;
F_l = day-of-burn litter fuel moisture, percentage by dry weight;
L_a = prefire loading of all aboveground biomass; $Mg{\cdot}ha^{-1}$;
L_l = prefire loading of litter biomass; $Mg{\cdot}ha^{-1}$;
L_n = prefire loading of nonshrub vegetation (grasses and forbs), $Mg{\cdot}ha^{-1}$;
L_s = prefire loading of shrubs (including saw palmetto), $Mg{\cdot}ha^{-1}$;
L_w = prefire loading of dead and down woody biomass; $Mg{\cdot}ha^{-1}$;
Season = season of burn, growing season burn = 1, all else = 0.
[b] Residual standard error from regression, in units of the dependent variable.

burned exceeded 85% on all flatwoods sites, with one exception (Table 5). Season of burning did influence consumption of the shrub fuels; greater consumption occurred for growing season (i.e., spring/summer) fires. Most (mean 86.1%) fine dead (dead saw palmetto, litter, and < 0.6 cm woody material) and fine live fuels (grasses and forbs) were consumed.

Model Variables

Models for estimating total fuel consumption and fuel consumption by fuelbed component (i.e., shrubs, herbaceous vegetation, dead and down woody material, and litter) were developed by using multiple linear regression (Table 7, Figure 3). Fuel loading and fuel moisture were only weakly correlated ($r < 0.49$ for untransformed

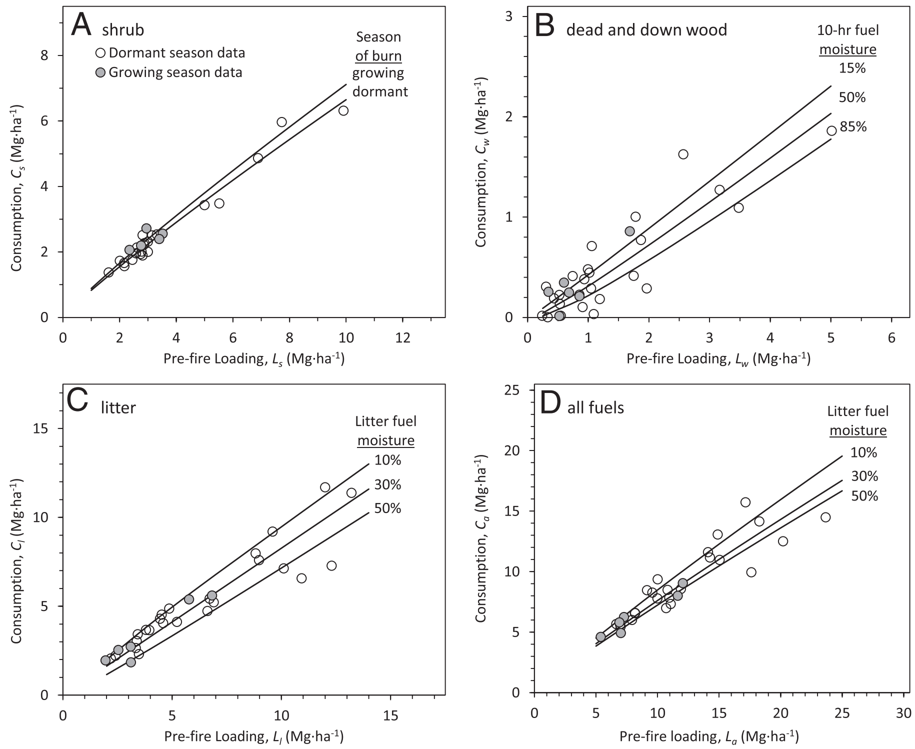

Figure 3. Multiple linear regression models showing: A) shrub consumption (including saw palmetto) as a function of prefire shrub loading and season of burn; B) dead and down woody fuel consumption as a function of prefire woody fuel loading for a range of values of 10-hour woody fuel moisture; C) litter consumption as a function of prefire litter loading for a range of values of litter fuel moisture; and D) total aboveground biomass consumption as a function of total aboveground prefire loading for a range of values of litter fuel moisture for pine flatwoods ecosystems.

Table 8. Pearson's correlation coefficient (r) matrix for dependent and independent variables used in flatwoods fuel consumption models. See Table 7 for symbol definitions.

	L_l	L_w	L_a	C_s	C_l	C_w	C_a	F_{10}	F_l	F_s
L_s	0.026	0.218	0.426	0.943	−0.030	0.255	0.326	−0.229	0.022	−0.085
L_l		0.760	0.895	0.024	0.937	0.602	0.863	0.313	0.454	−0.568
L_w			0.839	0.199	0.588	0.881	0.659	0.319	0.668	−0.396
L_a				0.401	0.794	0.721	0.914	0.252	0.487	−0.547
C_s					−0.017	0.239	0.365	−0.182	−0.016	−0.168
C_l						0.495	0.896	0.262	0.244	−0.586
C_w							0.627	0.168	0.503	−0.360
C_a								0.230	0.258	−0.628
F_{10}									0.679	−0.389
F_l										−0.264

variables) and, therefore, issues related to multicollinearity among predictors were avoided. Fuel loading was most strongly correlated with fuel consumption for all fuel categories for flatwoods sites (Table 8). Inclusion of some environmental variables improved model performance, although the improvements in model fit were small. Season of burn improved the model for shrub fuel consumption (increase in adjusted R^2 of 0.001), and inclusion of litter and 10-hour woody fuel moisture content also improved models for predicting litter (increase in adjusted R^2 of 0.024) and total dead and down woody fuel (increase in adjusted R^2 of 0.016) consumption, respectively. Including litter fuel moisture content improved the model for predicting total aboveground fuel consumption (increase in adjusted R^2 of 0.007). Nonshrub vegetation was almost entirely consumed in burned areas; nonshrub vegetation consumption was modeled as the sum of prefire grass and herbaceous vegetation loading multiplied by the average proportion consumed (i.e., mean 0.994 for sites in which $>$ 85% of the site burned), and the proportion of the area burned for the rare cases when the proportion of the area burned is $<$ 0.85.

Model Performance

Rather than dividing the data set for model development and model validation, the entire data set was used to develop the predictive models because of the modest sample size ($n = 30$). Instead, models were evaluated by comparing predictions to independently measured data (Table 9). Agreement between measurements and modeled estimates of fuel consumption were overall quite good (Figure 4). Modeled values were within 4.5–12.4% on average (root mean square error) for dormant and growing season fires, respectively, for the fires for which I had independently collected data

Table 9. Measured prefire loading, day-of-burn fuel moisture, and fuel consumption from independent data sets.

Data source[a]	Prefire loading					Day-of-burn fuel moisture			Measured consumption				
	Shrub	Herb.	Litter	Wood	Total	Shrub	Litter	10-hour	Shrub	Herb.	Litter	Wood	Total
	$Mg \cdot ha^{-1}$					%			$Mg \cdot ha^{-1}$				
Growing season													
Apalachicola 32	1.7	0.8	2.7	6.0	11.1	105	30	15	1.4	0.8	2.1	1.3	5.6
Apalachicola 71	1.1	0.8	4.0	4.0	9.8	120	40	40	0.9	0.8	2.8	0.0	4.5
Apalachicola 302	2.8	0.6	2.5	3.7	9.6	120	30	15	2.6	0.6	1.9	0.2	5.2
Eglin 100B-W	2.1	0.2	4.9	4.7	11.9	80	20	40	1.6	0.2	3.4	1.0	6.3
Eglin 103B-S3	3.9	0.6	4.0	7.5	16.0	95	35	40	2.5	0.6	2.9	0.3	6.3
Eglin 508A	2.7	1.8	3.1	8.5	16.1	95	30	50	2.3	1.8	2.4	0.7	7.2
Eglin 403B	1.9	1.1	3.2	4.6	10.8	105	40	20	1.0	1.1	1.9	0.4	4.4
St. Marks S3	8.9	0.5	2.7	4.3	16.5	130	35	40	8.1	0.5	1.9	0.3	10.8
Dormant season													
Okefenokee	7.2	0.3	2.3	3.3	13.0	100	25	45	4.7	0.2	2.2	1.3	8.4
Piedmont A	0.5	0.1	2.5	3.0	6.0	90	15	40	0.3	0.1	2.5	1.3	4.1
Piedmont B	0.3	0.5	2.3	2.5	5.6	100	20	50	0.1	0.5	2.3	0.9	3.9
Piedmont C	0.3	0.8	2.2	3.8	7.2	100	20	50	0.1	0.8	2.2	1.2	4.3
FL Panther 2	0.8	4.0	–	–	4.8	115	–	–	0.6	3.8	–	–	4.4

[a] J.B. Cronan, unpublished growing season data; R.D. Ottmar, unpublished dormant season data.

(R.D. Ottmar unpublished data, J.B. Cronan unpublished data). The models presented here produced more accurate predictions for individual fuel categories than those in operational use in the FOFEM v5.9 and Consume v3.0 software applications, although on summing estimates of fuel consumption by category, FOFEM did predict total site fuel consumption slightly more accurately (Figure 4).

Discussion

Consumption is determined by the amount of unburned, burned and fully combusted, and burned but only partially combusted fuel. Therefore, to accurately estimate overall fuel consumption for a burn unit, it is important to consider the proportion of the area that is actually burned as well as the amount of the prefire fuel that is fully and partially consumed.

Proportion of Area Burned

Horizontally continuous live and dead fine fuels contribute to high or complete burn coverage in pine flatwoods prescribed fires (Abrahamson and Hartnett 1990, Glitzenstein et al. 1995, pers. observ.). As a result, modeling the proportion of area burned may not be as critical for estimating overall fuel consumption and smoke emissions in flatwoods as in other shrub-dominated fuel types, such as big sagebrush (Wright and Prichard 2006) and Florida slash pine (*Pinus elliottii* Engelm. var. *densa* Little & Dorman) savannas dominated by wild guave (*Guettarda scabra* (L.) Vent.) and wax myrtle (*Myrica cerifera* L. (Small); Slocum et al. 2003), that experience patchier fire spread.

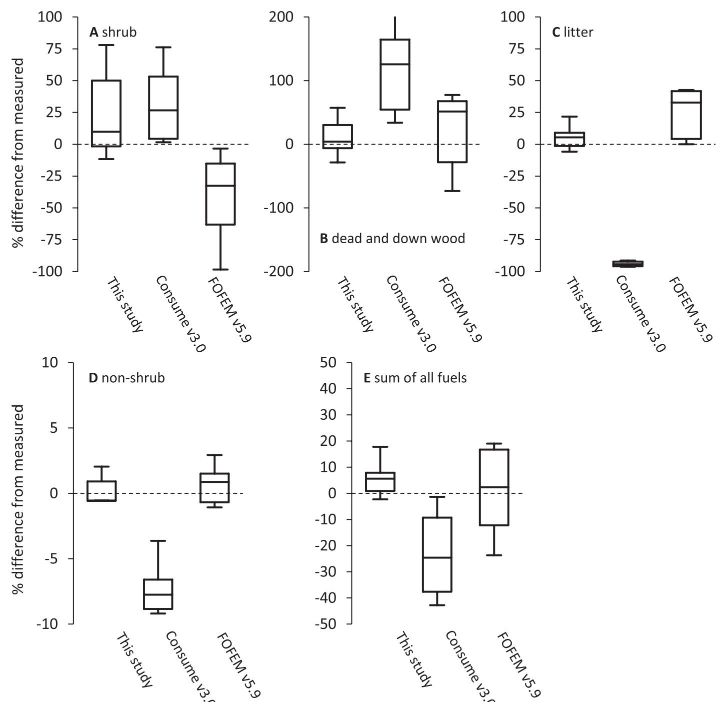

Figure 4. Difference from measured fuel consumption for predictions made with FOFEM 5.9, Consume 3.0, and the models reported in this study. Measured prefire fuel loading, day-of-burn fuel moisture, and fuel consumption are reported in Table 9.

Fuel Consumption

Prefire biomass was consistently the most important variable for predicting fuel consumption for all fuelbed components. Prefire biomass can be determined directly from field measurements using allometric (e.g., McNab et al. 1978, Gholz et al. 1999) or destructive methods, or it can be estimated using published guides (Southern Forest Fire Laboratory Staff 1976, Albrecht and Mattson 1977, Wade et al. 1993, Ottmar and Vihnanek 2000, Ottmar et al. 2003, Vihnanek et al. 2009) or expert knowledge. Fuel amount was the strongest predictor variable, but variation in fuel condition (i.e., live and dead fuel moisture content) and environment (i.e., season) increased or decreased fuel consumption, probably because of their effects on the energetics of the combustion process (Byram 1959, Hough 1968). This observation is similar to the results of Goodrick et al. (2010) who developed models for estimating consumption of the fuelbed as a whole (not by individual components) from measurements of prefire loading and various indices of the National Fire Danger Rating System (NFDRS; Deeming et al. 1977, Cohen and Deeming 1985) using data from prescribed fires at the Savannah River Site in South Carolina. Likewise, Reid et al. (2012) developed models for predicting litter and herbaceous fuel consumption in southern Georgia and northern Florida that included directly measured fuel variables, including combinations of litter and live herbaceous fuel moisture and fuel loading, and litter fuel density. In general, the models reported in this study and those of Goodrick et al. (2010) and Reid et al. (2012) predict more fuel consumption when fuel loading is higher and environmental conditions are drier.

Fuel moisture affects flammability and fire behavior, and is an important predictor of consumption for dead fuels (e.g., Hough 1978, Sandberg 1980). Intuition suggests that fuel moisture should also affect fuel consumption for live fuels. This study, however, found that live fuel moisture was generally not correlated with live fuel consumption for pine flatwoods. In this regard, the findings of this study agree with other research in shrub-dominated ecosystems that also failed to observe a relationship between live fuel moisture and live fuel consumption (Hough 1978, Bilgili and Saglam 2003, Wright and Prichard 2006). Reid et al. (2012), however, did present a model for litter fuel consumption in old-field upland longleaf, loblolly (*Pinus taeda* L.), and short-leaf (*P. echinata* Mill.) pine communities in northern Florida and southern Georgia that included live herbaceous moisture content as a predictor suggesting that further work is necessary to fully evaluate the effects of live fuel moisture content on fuel consumption.

Season of burn and weather have been shown to affect fire behavior, fire patchiness, fire effects, and vegetation response following fire (Bragg 1982, Brown 1982, Sparks et al. 2002, Slocum et al. 2003, Outcalt and Foltz 2004, Knapp et al. 2009), which suggests that they may also have an effect on fuel consumption. Season of burn was an important predictor of consumption of shrub fuels in flatwoods. Day-of-burn weather observations were not useful for predicting fuel consumption, although the inclusion of season in the prediction models may have effectively captured the long- and short-term fluctuations in weather and fire environment that instantaneous day-of-burn weather and fuel moisture measurements did not. Seasonal differences may represent a threshold effect on fuel consumption in a manner that different continuous observations of fire weather (i.e., temperature, relative humidity, days since rain, Keetch-Byram Drought Index, etc.) and fuel condition (live and dead fuel moisture content) cannot.

The models predicted fuel consumption for the independent flatwoods data very well (Figure 4). When compared to FOFEM and Consume, using the equations in Table 7 would produce more accurate estimates of all four fuel categories modeled. Comparatively, Consume overpredicted shrub and dead and down woody fuel consumption but underpredicted litter and nonshrub vegetation consumption. Because litter is such an abundant fuel type, Consume's large underpredictions of litter consumption caused large total aboveground fuel underpredictions in all cases. In contrast, FOFEM tended to underpredict shrub fuel consumption and overpredict dead and down woody fuel, litter, and nonshrub vegetation consumption. These over- and underpredictions, however, had the effect of canceling each other out, which resulted in FOFEM predicting total aboveground fuel consumption more accurately on average, although not as precisely.

Fire type (i.e., heading versus backing versus flanking) has a pronounced effect on fire behavior and may also influence fuel consumption (Sackett 1975). Experimental burning trials in saw palmetto-gallberry fuels in the southeastern United States (Hough 1968, 1978, Southern Forest Fire Laboratory Staff 1976) were equivocal with respect to differences in fuel consumption between backing and heading fires. The sites sampled for this study were burned during operational prescribed fires, and I had no control over how burn sites were ignited or the type of fire used in their burning. Given this limitation, I was not able to investigate whether fire type, lighting method, or firing pattern affected fuel consumption. Research on sites with similar fuels, fire weather, and burning patterns should be prioritized to better understand the drivers of fuel consumption and other fire effects in southern pine flatwoods and elsewhere.

The models presented here can be used to provide empirically based estimates of fuel consumption and changes in aboveground biomass in the postfire environment. In addition to providing information critical for assessing changes in fire hazard, fire risk (Wade and Lunsford 1989, Abrahamson and Hartnett 1990, Brose and Wade 2002), and air quality impacts (Hu et al. 2008, Tian et al. 2008), better estimates of fuel consumption are important for assessing heat, nutrient, and carbon fluxes and their impacts on vegetation dynamics and productivity (Gholz et al. 1985, Wade and Johansen 1986, Outcalt and Foltz 2004, Hiers et al. 2007).

Model Limitations

The models reported in Table 7 rely on statistical correlation among measurements so are empirical. As such, they do not model physical mechanisms directly, although predictors were considered only if a physically sensible explanation could be inferred. For example, consumption of litter and woody fuels in flatwoods decreases with increasing fuel moisture content as has been observed by others, and as one might expect from the principles governing ignition, pyrolysis, and combustion (Byram 1959). Although no wildfires were sampled for this project, the models should be applicable for wildfires, wildland fire use fires, and prescribed fires, in which the fuel characteristics and environmental variables fall within the range of the data used to develop the models.

Dead and down woody fuel loading was sparse throughout the sites sampled for this study and also limited in the independent test data set. Thus, while the dead and down woody fuel consumption model was quite accurate for cases where dead and down woody fuels are concentrated in the smaller size classes (i.e., <7.6 cm in diameter), it is likely that our model will tend to overpredict woody fuel consumption in forests with heavier loading, particularly of larger (i.e., >7.6 cm in diameter) logs. Users would be prudent to rely on FOFEM and Consume when evaluating forests with substantial loading of dead and down wood.

Management Implications

In the southeastern United States, land managers use prescribed fire as a tool to achieve a wide variety of objectives, including fuel, fire hazard, and fire-adapted species management; restoration and maintenance of ecosystem structure and function; and control of insects and pathogens (Wade and Lunsford 1988, Wade et al. 2000, Varner et al. 2005). Regardless of fire's many beneficial effects, however, combustion of forest fuels does produce smoke that can negatively affect air quality, visibility, and human health and safety. This study quantified the conditions that are related to fuel consumption in pine flatwoods fuel types that have a substantial live shrub component and proposes models to better evaluate the likely effects of fire under a range of conditions. These models will allow fire managers to generate estimates of fuel consumption and the resulting emissions without having to rely on decision support software that extrapolates from unrelated data or undocumented expert opinion. The ability to predict the consumption of live and dead fuels under different burning conditions will allow fire practitioners in pine flatwoods fuel types to better plan for and, if necessary, mitigate the effects of prescribed fires and anticipate the effects of wildfires.

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