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RESEARCH ARTICLE

Spatial patterning of fuels and fire hazard across a central U.S. deciduous forest region

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Abstract Information describing spatial and temporal variability of forest fuel conditions is essential to assessing overall fire hazard and risk. Limited information exists describing spatial characteristics of fuels in the eastern deciduous forest region, particularly in dry oak-dominated regions that historically burned relatively frequently. From an extensive fuels survey of unmanaged forest lands (1,446 plots) we described fuel loadings and spatial patterns of fine and coarse fuels. We attempted to explain the variability in fuel loading of each time-lag fuel class using landscape and seasonal variables through a multiple regression modeling approach. Size class distributions of woody fuels were generally homogeneous across the region except in the glaciated portions of Illinois where loadings appeared lower. Temporally, litter depths progressively decreased from leaffall (November). A fire hazard model that combined seasonal changes in litter depth and fuel moisture content depicted the degree of regional spatial variability during the transition between extreme dry and wet conditions. In the future, fire hazard indices could be paired with ignition probabilities in order to assess spatio-temporal variability of fire risk within the region.

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Introduction

Forest fuels management is a global fire issue (Canadian Wildland Fire Strategy Project Management Team 2006; Gould 2006; Xanthopoulos et al. 2006), particularly in the United States (Andrews and Butler 2006). In the U.S. the Fuel Characteristic Classification System (FCCS) is a comprehensive tool to catalog, classify, and compare fuelbeds (Ottmar et al. 2007). Recently, due to increased interest in forest carbon stocks, the FCCS and fuels studies have expanded relevance beyond fire management (Heath et al. 2011). Despite growing interest in fuels information, relatively few characterizations of regional-scale fuel variability have been made in the eastern U.S. This information would be particularly relevant to dry oak forest regions where historically fire was frequent and presently many restoration efforts utilize landscape-scale prescribed burning.

Within the drier, western portion of the U.S. Central Hardwoods forest region, studies pertaining to fire science are relatively abundant. These include fuel loading (Crosby 1961; Shifley et al. 1997; Kolaks et al. 2003; Stambaugh et al. 2006), fire behavior and effects (Grabner 1996; Grabner et al. 2001; Kolaks et al. 2003; Hartman 2004; Shang et al. 2004; Stambaugh et al. 2007; Stevenson 2007; D. Swanson unpublished data), and ignitions and fire risk (He et al. 2004; Shang et al. 2004; Brosofske et al. 2007; Stambaugh et al. 2007). Although fuels have be characterized at different sites a regional analysis is lacking and would provide a better context for understanding factors controlling spatial and temporal patterns in the fuel (fire) environment. For fire management, this information would be useful for monitoring regional forest fuel conditions with respect to fire hazard and risk and for estimating fire effects such as smoke impacts, soil heating, and tree mortality.

Surface fuel is the most important fuel layer for fire regimes of eastern U.S. deciduous forests. Fire propagation relies on a continuous surface fuel bed and much of the energy released (i.e., fire intensity) results from flame combustion of fine fuels such as litter (i.e., leaves, stems) and 1-h fuels [i.e., twigs <0.64 cm (0.25 in) diameter] (Kolaks 2004). In forests, litter fuels can be effectively replenished within a few years during which potential fire spread rates and flame lengths rapidly change (Stambaugh et al. 2006). Measurements of hardwood litter are commonly reported as depths, however relating litter depth to loading can be difficult because litter bulk densities can be highly variable (Ottmar and Andreu 2007; Ottmar et al. 2007) due to factors such as litter type, litter age, and repeated compression and expansion during wetting and drying (Crosby and Loomis 1974).

The objective of this study was to describe and model changes in fuel patterning and fire hazard of a large region of the drier, western portion of the Central Hardwoods forest region. Fire hazard is defined as the amount, type, condition, and arrangement of fuels (Hardy 2005). In this paper we (1) describe the spatial variability in fuel loading, (2) identify the mechanisms and parameterize a model describing temporal and spatial patterning of litter depths and, (3) present model results of estimated changes in fire hazard considering seasonality and drought conditions.

Methods

Study area

The study region lies in the central U.S. and consists of the southern portions of Missouri, Illinois, and Indiana (Fig. 1). The study region covers approximately 190,000 km^2 and is delineated by the Ozark Highlands and Interior Lowland Plateau ecoregions (Bailey 1998; Nigh and Schroeder 2002). Within the region are large contiguous areas of forest including three National Forests. All states have significant areas of forestland managed by state and federal agencies and all have a majority of private landownership. From northwest to southeast annual mean precipitation increases from about 92 to 138 cm (Daly et al. 2004). Timing of the annual growing period is relatively consistent throughout the region with leaf and stem growth initiating in approximately late-March to early April and continuing until approximately early to mid-September. The primary leaffall timing is variable by a few weeks and often influenced by the first fall season freeze event. Leaffall is a gradual process consisting initially of small inputs that increase to a primary leaffall period typically occurring in mid-October to early-November and lasting a few weeks. Coincident with leaffall can be an increased input of other fine fuels [<7.62 cm (3 in) diameter] (S. Pallardy, unpublished data) while input of larger fuels is probably more consistent throughout the year and dependent on disturbance events and tree mortality rates.

Fuel loading survey plots

Fuels data were collected during the period of June 2004 to January 2006. Fuels data were collected exclusively from forests in the study area; therefore the results may not pertain to the fuel loading within other regions or land use types (e.g., agricultural lands, grasslands, and urban areas). Ownerships included state lands, national forest lands, and state and county parks. Fuels data were collected at plots located along transects that crossed multiple topographic positions. All plots were located in areas that had no forest management during approximately the last 50 years. Approximately 15 plots had evidence of recent (last 50 years) natural disturbances and

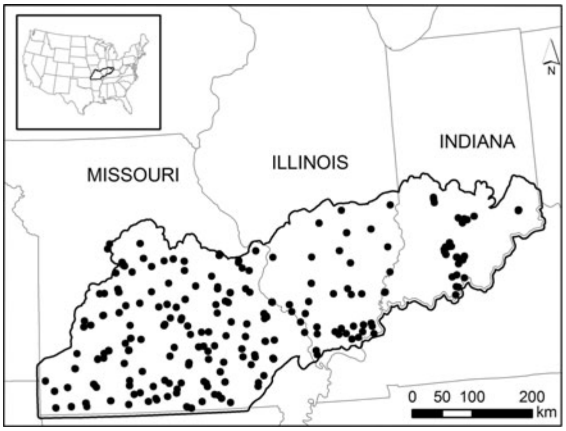

Fig. 1 Study area (*bold line*) consists of southern portions of Missouri, Illinois, and Indiana. *Black dots* represent the location of transects ($n = 228$) along which multiple fuel loading plots (total = 1,446) were sampled. *Inset*: study area within the conterminous U.S.

notes were taken describing the extent of disturbance. Transects were randomly located in public ownerships utilizing a random point generator and ESRI® ArcGIS™ v 9.1 (ESRI 2005) (Fig. 1). Transect bearings were randomly chosen from a predetermined bearing range that ensured transects crossed landforms and varied in slope, aspect, and vegetation. Fuel plots were located at 75 m intervals along transects. Fuel plot design followed guidelines developed by Brown (1974) with modification. Modifications were (1) solid and rotten 1,000-h fuels were undifferentiated and (2) no fuels were removed from plots. We did not measure grass fuels or shrubs because in these unmanaged forests grasses and shrubs are commonly absent or of minimal importance. Similarly, duff was not considered in our survey because duff is minimal, often absent, and contributes little to total fuel loading. We recorded mean litter depth (cm) at each fuel plot based on 12 measurement points along fuel transects. Three to ten fuel plots were sampled along each transect depending on the size of forested area and variability in landforms. This resulted in transect lengths ranging from 225 to 750 m in length. A total of 158 transects (1,030 plots) were sampled in Missouri, 36 transects (205 plots) in Illinois, and 34 transects (211 plots) in Indiana (Fig. 1). A total of 228 transects (1,446 plots) were sampled across the region. Transect and plot were located with a GPS and transferred with fuel loading data into ArcGIS.

Brown's (1974) fuel plot methodology was designed to record fuels in four diameter size classes that correspond to rates of change in moisture content: 1-h: 0.0–0.64 cm (0.0–0.25 in), 10-h: 0.66–2.54 cm (0.26–1.0 in), 100-h: 2.55–7.62 cm (1.01–3.0 in), and 1,000-h: > 7.62 cm (3 in) (Cohen and Deeming 1985). This method requires fuel loading constants that adjust fuel weights based on their slope, specific gravity, and mean size class diameters. We derived fuel loading constants from several sources including other published studies (Brown 1974; Adams and Owens 2001) and lab measurements of fuels characteristics (e.g., quadratic mean diameters, specific gravity).

In addition to fuel measurements, at each plot we measured plot slope, aspect, slope shape and position, basal area, ground cover (leaves, needles, herbaceous plants, bare soil), number of standing snags ≥7.63 cm (3 in) dbh, and density of small diameter [<7.63 cm (3 in) dbh)] trees. Notes were taken to describe any evidence of disturbance, particularly past evidence of fire. Additional plot attributes were spatially joined to the fuel plot dataset using GIS and included: elevation, mean annual precipitation and temperature (Daly et al. 2004), topographic roughness index (Stambaugh and Guyette 2008), landcover class (Homer et al. 2007), road density, and geographic coordinates.

Fuel loading calculations were made from counts of fuel intercepts and fuel sizes using equations described in Brown (1974). Summary statistics of fuel loading were generated for the entire study region and subregions by states. Fuels were described by time-lag class and reported in both tons per acre (tons ac^{-1}) and megagrams per hectare (Mg ha^{-1}) since both are widely used and weight units. Frequency distributions of fuel loading by time-lag class by state were compared in order to judge whether major differences occurred between states. Regional and plot-level fuel loading trends were examined using maps and scatterplots of data; both which guided our approach towards developing models of fuel loading and litter depth.

Modeling fuel loading and litter depth

The purpose of the model exercises was to determine if variation in fuel loadings could be explained from ecological, plot, and social characteristics (Table 1).

We wanted to develop relatively simple models whose relevance could be validated both statistically and biologically. We attempted to develop models with individual fuel classes and their combinations as potential predictands. Fuel plot data were excluded from the analysis when there was evidence of recent fire and when plot litter was dominated by eastern redcedar (*Juniperus virginiana*) needles as this fuelbed has very different characteristics (M. Stambaugh, unpublished data). Multiple regression analysis (SAS/STAT 2002) was used to (1) identify significant relationships between fuel loading and predictor variables (Tables 1, 2) parameterize a final model that was used to depict landscape variability in litter depths—a similar approach as Chojnacky et al. (2004) and Reich et al. (2004). A variable describing fuel residence time was defined as the number of months between the fuel collection date and the previous November (i.e., leaffall). Variables were allowed to enter models at the significance level of $P < 0.01$. Bootstrap methods were used (100 iterations, with replacement) to assess parameter and model stability. Final model selection was based on bootstrap results (i.e., model stability and *r*-square). Model validation was achieved by regressing actual fuel loading values against predicted values for an unused randomly selected portion of the dataset ($n = 551$).

Fire hazard index

We developed a fire hazard index that considers the combined effects of litter depth and drought. The index is a modification from typical fire hazard definitions in that it considers litter moisture content as an indicator of the relative probability of fires starting and spreading. The index was calculated as a function of litter depth and moisture content whereby deeper and drier litter represented increasing index values. We assumed that increased litter depths represented either increased litter loading or a litter layer with low bulk density; both of which we assumed equaled higher fire hazard. Similarly, we assumed lowered litter moisture contents equaled higher fire hazard due to the increased potential for ignition and increased rate of combustion. The spatial variability in litter moisture content was described using a model that estimates percent moisture content from aspect and drought condition (Stambaugh et al. 2007). In this study fuel moisture contents were described by drought conditions utilizing divisional Palmer Drought Severity Indices (Palmer 1965; National Climate Data Center 1994). Litter moisture content and the fire hazard index were described through a transition of three levels of drought (moderately wet, PDSI = 1.43; near normal, PDSI = −0.66; mild dry, PDSI = −1.95). We excluded models depicting extreme wet and dry conditions because (1) drought-aspect-moisture content models are not available for these extremes, and (2) during these extremes litter moisture contents are homogeneous across the landscape and fire hazard is either obviously very low (extreme wetness) or very high (extreme drought) regardless of aspect. Maps depicting fire hazard during the transition from one moisture extreme to the other are expected to be more spatially complex and useful for depicting spatial variability. In summary, final fire hazard maps were created to display combined effects caused by month of year (i.e., time since leaffall) and changing drought condition.

Results

Fuel loading from survey plots

State-level fuel loading tended to be very similar throughout the study region (Table 2; Fig. 2). Fuel loading means for fine fuels (i.e., 1- and 10-h) were nearly identical. Overall, mean woody fuel (1- to 1,000-h class) loading was slightly higher for Indiana and Missouri than for Illinois. Mean woody fuel loading was 9.78 Mg ha^{-1} (4.37 tons ac^{-1}) for the entire study region (Table 2). Mean woody fuel loading was two times higher in Indiana and Missouri than Illinois—a difference primarily due to coarser fuels (i.e., 100- and 1,000-h). Missouri had the highest recorded woody fuel loading (153.2 Mg ha^{-1}; 68.4 tons ac^{-1}) followed by Indiana (123.6 Mg ha^{-1}; 55.2 tons ac^{-1}) and Illinois (74.8 Mg ha^{-1}; 33.4 tons ac^{-1}) (Table 2).

Frequency distributions showed that woody fuel loading was generally positively skewed within timelag classes (Fig. 2). Distribution forms appeared very similar among the three states. Loadings of 1- and 10-h timelag fuels tended to be more normally distributed compared to 100- and 1,000-h timelag

Table 1 Parameters used in multiple regression analysis to predict litter depths across the western portion of the Central Hardwood forest study area

	Description	Units	Source
Ecological variables			
TRI	Topographic roughness, surface area ratio	Indices	Stambaugh and Guyette (2007)
Precip	Mean annual precipitation	30-year avg. (cm)	PRISM data; Daly et al. (2004)
Landcov	Landcover type	Categorical	National Land Cover Database
Mmaxt	Mean maximum temperature	30-year avg (°C)	PRISM data; Daly et al. (2004)
Elev	Elevation	*m*	National Elevation Database
Slope	Slope	Degrees	National Elevation Database
Spp_comp	Species composition	Categorical	
Plot variables			
Plot number	Sequence of plot sampled	#	Plot data
Transect number	Sequence of transect sampled	#	Plot data
X Coordinate	Geographic coordinates of plot	UTM	GIS
Y Coordinate	Geographic coordinates of plot	UTM	GIS
Residence time	Months since leaf fall (October)	#	Plot data
Social variables			
State	State name	Categorical; 3 classes	US Census Bureau
Road_dens	Road density	km/km^2	US Census Bureau

fuels which tended to decrease exponentially with size (Fig. 2). For all plots combined, mean woody fuel loading increased by 2–3 times with each increase in timelag fuel class. The number of plots observed having no woody fuels also increased with fuel size class. The majority of plots had no fuels in the 1,000-h timelag class (Fig. 3).

Woody fuel loadings showed several notable spatial patterns (Fig. 4). Loadings in Missouri and Indiana had the highest variability. One-hour fuel loading was highest in southern Missouri and lowest in Illinois (north of the Shawnee Hills). Spatial variability in 10-h fuels appeared similar across all states. One-hundred hour fuels were least along the western portion of the study region and in Illinois. One-thousand hour fuel loading was greatest in southeastern Missouri and in the unglaciated portion of southcentral Indiana. Although some fuel plots in Illinois showed 1,000-h fuel loading variability similar to Missouri and Indiana, most plots had less than average fuel loadings for this fuel class.

Fuel loading and litter depth from models

Model attempts to estimate woody fuel loading from ecological, plot, and social parameters (Table 1) showed no predictive ability. Only a model of litter depth produced a statistically significant and biologically relevant model. The final litter depth model (r-square = 0.36) predicted litter depth from five parameters: residence time (number of months since leaf fall (November)), topographic roughness index, elevation, precipitation, and slope exposure (Table 3; Fig. 5). Bootstrap results showed that model prediction was relatively stable with model r-square values ranging from 0.31 to 0.40. Of the model parameters, litter 'residence time' (i.e., months since leaffall) had the greatest explanatory power (partial $r^2 = 0.22$), while slope and precipitation had the least. The model suggests that the conditions associated with highest litter depths are periods immediately following leaffall in landscapes with high topographic roughness and annual precipitation, and sites in higher elevations and steeper slopes.

The spatial pattern of litter depth varied greatly throughout the course of a year (Fig. 5); predicting that litter depths annually vary by up to 3.5 cm in any location. During any given month, the model predicts that litter depth can vary by up to 4.7 cm within the study region. Overall, the southern Ozarks of Missouri and unglaciated portions of Indiana showed the largest areas of increased litter depths. Glaciated

Table 2 Woody fuel loading summaries of the study area and individual states

	1-h	10 h	100 h	1,000 h	Total
Fuel loading (Missouri, Illinois, Indiana)					
Count	1,446	1,446	1,446	1,446	1,446
Min	0.00	0.00	0.00	0.00	0.00
Max	0.62	1.52	8.86	67.10	68.40
Mean	0.12	0.25	0.97	3.03	4.37
St. Dev.	0.07	0.16	0.85	6.41	6.65
Skewness	1.39	1.91	2.39	4.10	3.86
Kurtosis	6.94	11.69	14.74	25.31	22.95
1st Quart.	0.07	0.13	0.37	0.00	1.00
Median	0.01	0.25	0.75	0.00	2.10
3rd Quart.	0.16	0.31	1.27	3.30	4.80
Fuel loading (Missouri)					
Count	1,030	1,030	1,030	1,030	1,030
Min	0.00	0.00	0.00	0.00	0.00
Max	0.62	1.52	8.86	67.12	68.44
Mean	0.13	0.25	1.02	3.16	4.56
St. Dev.	0.08	0.16	0.91	6.53	6.82
Skewness	1.33	2.13	2.44	3.97	3.71
Kurtosis	6.45	12.99	14.46	24.11	21.56
1st Quart.	0.07	0.13	0.37	0.00	1.04
Median	0.12	0.25	0.75	0.00	2.21
3rd Quart.	0.16	0.31	1.47	3.59	5.23
Fuel loading (Illinois)					
Count	205	205	205	205	205
Min	0.02	0.00	0.00	0.00	0.10
Max	0.30	0.68	2.60	32.70	33.40
Mean	0.11	0.24	0.76	1.66	2.77
St. Dev.	0.05	0.13	0.56	4.20	4.33
Skewness	0.79	0.85	0.70	4.41	4.28
Kurtosis	3.79	3.69	3.21	25.52	24.06
1st Quart.	0.07	0.13	0.37	0.00	0.80
Median	0.09	0.25	0.73	0.00	1.40
3rd Quart.	0.14	0.31	1.11	1.80	3.13
Fuel loading (Indiana)					
Count	211	211	211	211	211
Min	0.00	0.00	0.00	0.00	0.19
Max	0.25	0.87	4.73	54.11	55.15
Mean	0.10	0.26	0.92	3.72	5.00
St. Dev.	0.05	0.15	0.74	7.39	7.43
Skewness	0.68	1.02	1.52	3.94	3.84
Kurtosis	3.26	4.51	7.13	22.47	21.69
1st Quart.	0.07	0.13	0.37	0.00	1.13
Median	0.09	0.25	0.75	1.33	2.71
3rd Quart.	0.14	0.33	1.15	4.14	5.61

Loadings are given in tons ac^{-1} and are converted to Mg ha^{-1} by multiplying by 2.24

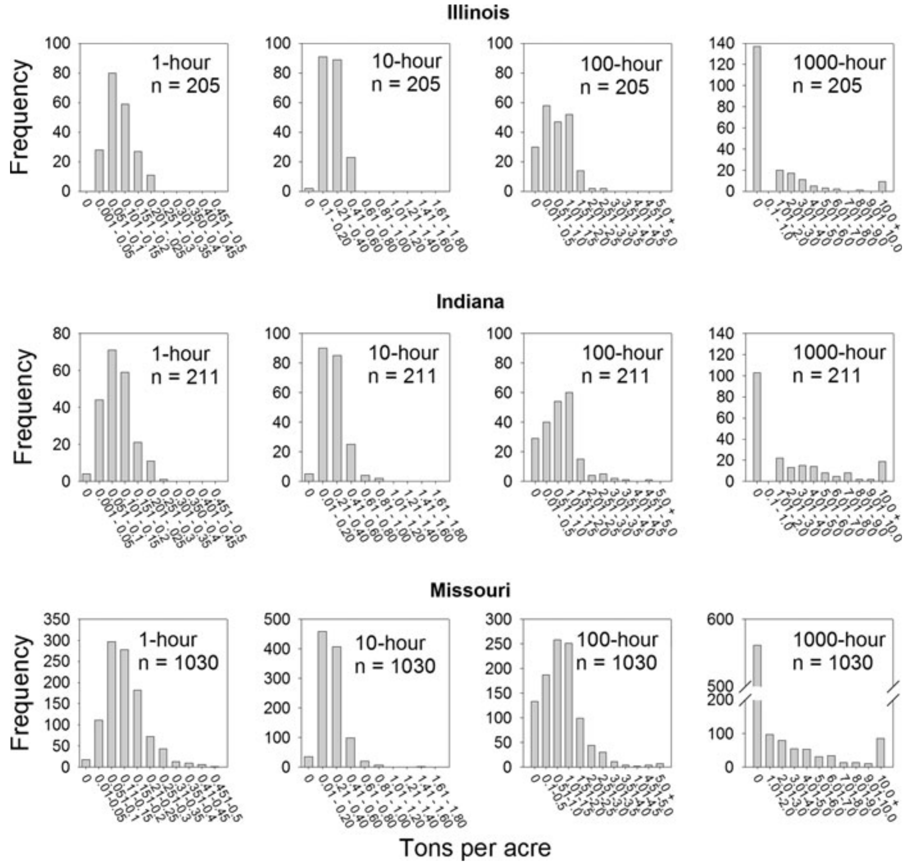

Fig. 2 Frequency distributions of fuel loading (tons ac^{-1}) of fuels in four time-lag classes for Illinois, Indiana, and Missouri. (Convert to Mg ha^{-1} by multiplying by 2.24)

regions, particularly in Illinois, showed lowest litter depths as did large river corridors. Despite intra-annual variability due to leaffall and decomposition the general spatial pattern of litter loading variability appeared to be consistent throughout the year and all areas decreased in litter depth following leaffall (Fig. 5).

Fire hazard

Following conventional ideas about the regional fire environment, the fire hazard model appeared to accurately portray changes due to season and drought condition. That is, fire hazard decreased as conditions changed from dry to wet (Fig. 6). Also, due to leaffall and decomposition, fire hazard was highest in November (leaffall) and further decreased through March and July. During mild dry conditions, the spatial pattern in fire hazard was not significantly changed by litter through the course of the year. However, during incipient wet conditions, changes in month (litter residence time) showed to have a greater influence on fire hazard. Changes in fire hazard between incipient wet and mild dry conditions were greater for the month of July than for November or March. A review of the simulated hazard maps shows that incipient wet conditions in July represent the lowest hazard while mild dry conditions in November represent the highest hazard conditions (Fig. 6). Within the range of drought conditions considered (i.e., no extremes) the greatest fire hazard is estimated to occur during mild drought conditions during November, particularly in areas of southwestern Missouri (Fig. 7).

Discussion

The litter depth model shows comparable skill to other eastern U.S. landscape fuel models. Chojnacky et al. (2004) explained 30% of the variance in litter across the eastern U.S. Precipitation was the only model parameter common between our model and Chojnacky et al.'s. In addition, they found geographic

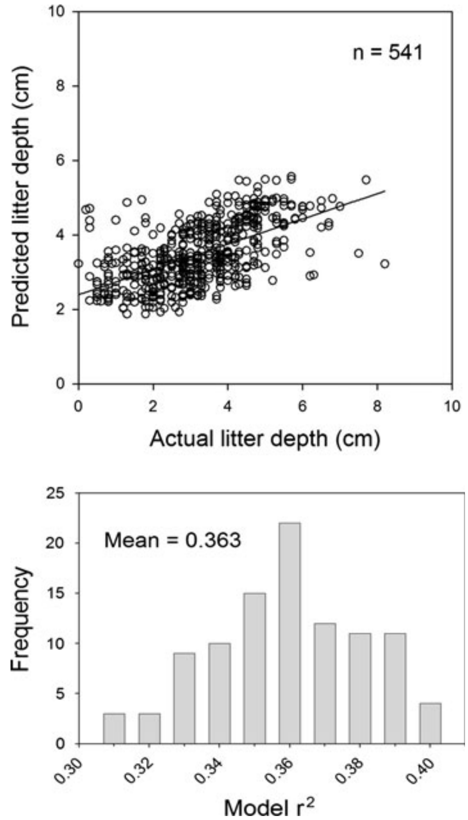

Fig. 3 (*Top*) Scatterplot of actual versus predicted litter depths generated from the multiple regression model (Table 2). (*Bottom*) Bar plot of bootstrap results of the model *r*-square for 100 iterations

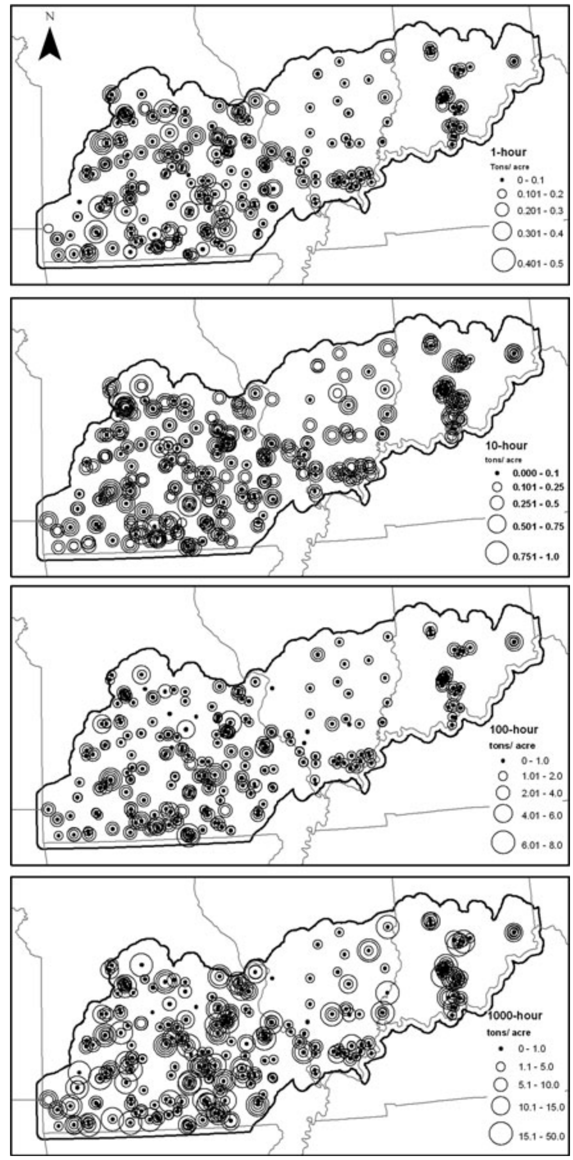

Fig. 4 Spatial patterning in fuel loading for the four time-lag fuel classes. *Circle* locations correspond to transect locations. Increasing circle sizes correspond to increasing fuel loading (see legend). Ranges of *circle sizes* represent the ranges of observed fuel loading along transects. (Convert to Mg ha^{-1} by multiplying by 2.24)

coordinates to be significant which we did not. The seemingly low predictive ability of our litter depth model may be a consequence of the low degree of landscape-level controls (elevation, topographic roughness) on litter variability. Furthermore, differences in the deciduous-dominated vegetation of the study region or possibly the strong temporal leaffall influence may mask influences associated with ecological, plot, or social variables.

The litter depth model estimates and maps should be considered a temporal "snapshot" generated from regional trends that vary with site specific factors such as time since local small- and large-scale disturbances and changes in forest density and species through succession. In terms of litter depth, the most contrasting forested landscapes are the central Ozark Highlands of Missouri, the unglaciated region of Indiana, and the glaciated portions of Illinois (Fig. 5). Overall, the highest litter depths were in the southwest portion of the study region and decreased to the northeast. Generally, Chojnacky et al. (2004) found the same patterns in litter loading including counties in the central Missouri Ozark Highlands having the highest loading. From this similarity it is suggested that the litter depth map presented here reflects patterning in actual loading (as opposed to just depth). Certainly, one of the

Table 3 Parameter estimates for a multiple regression model predicting litter depth (cm) in the western Central Hardwoods forest region

Model	*n*	r^2	*F* value	*P* level
(A) Regression results	557	0.363	63.03	<0.0001
Parameter	*B*	SE of *B*	*p* level	Partial r^2
(B) Regression coefficients				
Intercept	−29.127	7.802	0.0002	
Residence time	−0.743	0.059	<0.0001	0.223
Topographic roughness	29.109	7.880	0.0002	0.070
Elevation	0.004	0.0006	<0.0001	0.042
Slope	0.031	0.008	0.0002	0.017
Precipitation	0.003	0.0008	0.0037	0.009

y = *litter depth* (cm), *residence time* = natural log of months since November, *topographic roughness* is an index of topographic variability (Stambaugh and Guyette 2008), *elevation* = meters a.s.l., *slope* = degrees, *precipitation* = mean annual precipitation (mm)

seeming weaknesses of this study is that litter is reported in depths and not weights. Due to time and support, it was not operationally possible for us to collect meaningful (i.e., dried, replicated) litter weights from the 1,446 plots in the study region. It is difficult to convert litter depths to loadings using bulk densities due to the many factors influencing the litter layer (Ottmar and Andreu 2007). Despite these limitations, we feel that litter depths are an excellent indicator of fire hazard for two reasons: (1) increased litter depths equate to higher fire hazard because there is more fuel available to support the combustion reaction, (2) litter depths were positively correlated with woody fuel loading and could be an indicator of total woody fuel loading, (3) should increased litter depths be due to vertical expansion, then increased litter depths still equate to increased fire hazard because a vertically expanded ("fluffier") litter layer can dry more rapidly and within the litter layer is more oxygen promoting a faster rate of combustion.

Increases in fire hazard indices were represented by increased litter depths and decreased litter moisture contents. From reviewing the fire hazard maps (Fig. 6) the model suggested that incipient wet conditions in July represent the lowest hazard while mild dry conditions in November represent the highest hazard. Although the results are intuitive it is important to verify that the model is predicting conditions that are biologically accurate. Areas of high fire hazard appeared to be more strongly linked

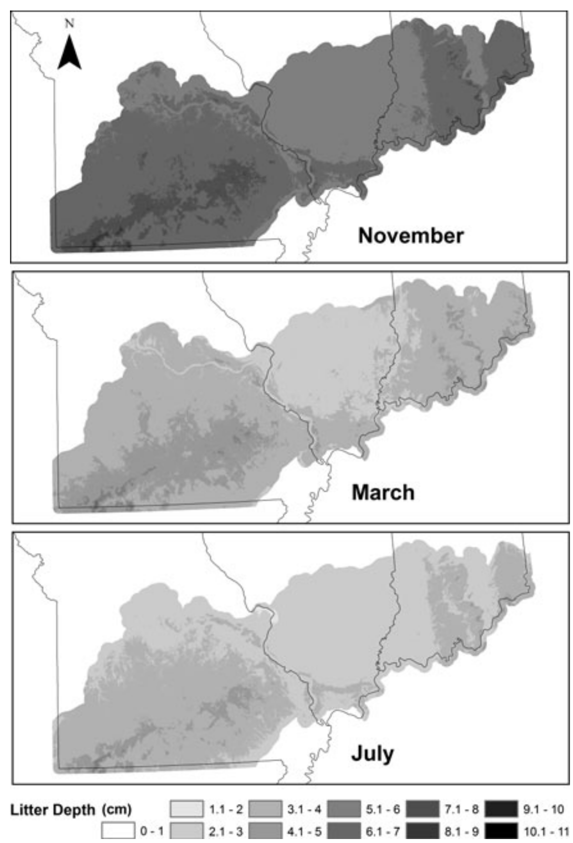

Fig. 5 Litter depth model estimates for equally spaced months during the year. Maps decrease in regional litter depth according to residence time (i.e., months since leaffall, November)

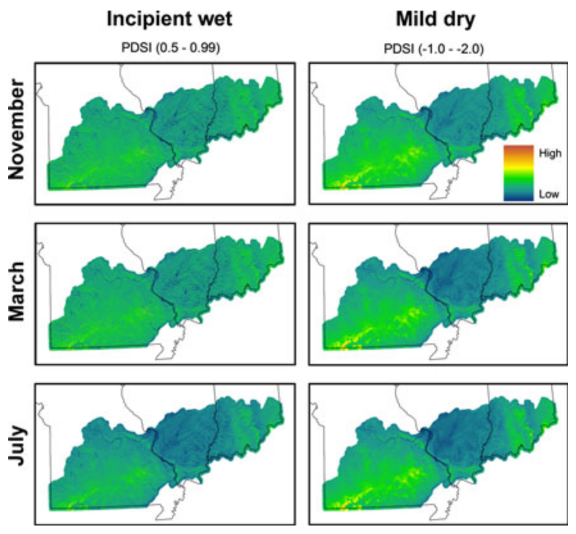

Fig. 6 Maps of fire hazard for three equally spaced months during incipient wet and mild dry conditions

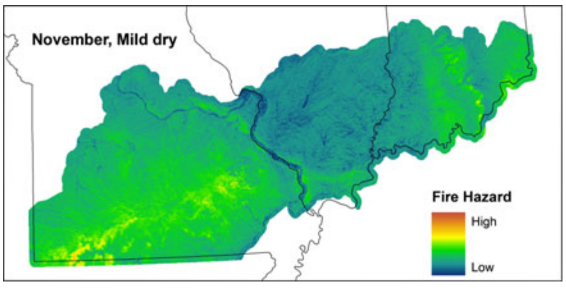

Fig. 7 Enlarged November fire hazard map. This condition represents the highest fire hazard condition predicted by the model. Fire hazard would further increase with increased drought, however less spatial complexity is expected as fuels become homogeneously dry regardless of aspect

to drought conditions than month of year. For example, the area of highest hazard (located in southeastern Missouri) (Fig. 6) does not appear to diminish as month of year is altered. Here it appears that drought condition is the dominant factor. Although drought is known to be an important determinant of fire hazard, less is known about its spatial variability, particularly as it relates to changes in the litter layer.

One of the most important results was the identification of leaffall (residence time) as an important control on litter depth and fire hazard. Regression analyses suggested its influence is greater than that of any other factor including topography or climate. We are not aware of any large-scale fuel modeling efforts that have included time since leaffall as a model parameter, but in deciduous forests this makes biological sense. In Kentucky, Lyons et al. (2006) described rapid reaccumulation of leaffall after a prescribed burn that significantly reduced fuels. In Ozark forests, litter can fully reaccumulate after approximately 12 years with 75% accumulation expected within about 4 years (Stambaugh et al. 2006). Understanding of the rates of accumulation and decomposition will likely prove significant when identifying large-scale patterns of leaf litter loading (Chojnacky et al. 2004), while other factors such as slope, stand age and basal area may have much less importance (Woodall et al. 2007).

Many factors could be responsible for the high degree of unexplained variance in the litter model. Species and physical and chemical leaf composition substantially alters litter characteristics (Kucera 1959; Melillo et al. 1982). Oak leaves have higher lignin composition than maples and elms, which can cause them to persist longer in the leaf layer. Leaf curling, particularly in oaks, can give the leaf layer greater vertical structure and aeration while other species such as elms and maples lie flat and have less mass. Following leaffall events, litter depths decrease due to decomposition, but also due to compaction. Variability in litter depth can be caused by differences in leaf compaction that occurs from precipitation that varies among climatic regions. Compared to rain, when precipitation is in solid form (i.e., snow, ice) the above-layer weight can be increased and compaction duration lengthened. When snow covers and compacts litter the decomposition may not necessarily be slowed or delay litter decay. Studies monitoring soil respiration in the northern Ozarks suggest litter decomposition is continued despite snow cover and that snow cover may enhance litter decomposition during winter as it provides a thermal barrier from ambient temperatures promoting the microbial activities responsible for decomposition (K. Hosman, personal communication). Litter decomposition may be associated with many other factors as well such as species composition and mixes (Hansen 1999; Gartner and Cardon 2004), soil nutrient dynamics (McClaugherty et al. 1985; Washburn and Arthur 2003; Demchik and Sharpe 2004), climate (Aerts 1997), and regional differences in litter response following disturbance (Blair and Crossley 1988).

Patterning in larger fuels

Fire hazard estimates may be even greater than predicted once the woody fuel loadings are considered. Overall, loadings found for 1- through 1,000-h fuels were comparable to those reported for other similar eastern U.S. deciduous forest types (Woodall et al. 2007). Unfortunately, parameterization of a model estimating woody fuel loadings has proven unsuccessful and woody fuels were not utilized in the fuel hazard assessment. In an analysis of eastern U.S., Chojnacky et al. (2004) similarly showed that models of woody fuel loading consistently had lower explanatory power compared to models estimating litter. Temporally, woody fuel input can be sporadic or constant (Rochow 1974). Although leaffall events can correspond with twigfall, the degree of this 1-h fuel input suggests being lower and less predictable. For 10- to 1,000-h fuels, field and sampling experience indicated that these fuels are best described as randomly distributed- both temporally and spatially. This was particularly the case at a site-level scale where adjacent fuel plots had dramatically different woody fuel loading, particularly due to 100- and 1,000-h fuels. At very broad scales, increased patterning may exist and be associated with broad vegetation types or climate divisions (Woodall and Liknes 2008).

Many models of woody fuels include broad forest characteristics such as stand age or disturbance as an important control of loading variability (Pregitzer and Euskirchen 2004). Assuming many of the forests that were sampled were second-growth regenerated from early twentieth century logging or earlier (this appeared to be the case), greater variability in fuel loading may be expected as greater successional ages are attained (Ryu et al. 2004). In the study region, variability in fuels due to disturbance can occur from single-tree to region-wide events (e.g., May 2009 derecho event). It seems plausible that increased disturbance severity results in increased patterning of larger fuels. Since 2006, ice storms and windstorms in southern Missouri and windstorms in Illinois may have dramatically increased fuel loading above levels reported here.

A broad region of low litter depths and fuel loading existed in forests located in the glaciated (northern) portions of Illinois (Fig. 3)—a highly agricultural landscape. Interestingly, the region tended to show lowered fuel loading for all time-lag classes except for the 10-h fuels. Currently, it is not clear why this pattern existed, but it could be due to younger forest ages or varied species composition. An association to agricultural lands does not appear to be a consistent attribute of areas with lowered fuel loading. It may be possible that decreasing the extent of analyses to smaller regions could reveal significant differences in woody fuels attributes associated with landtypes, however previous comparisons of fuel loading among Missouri ecological landtype associations did not reveal significant differences in woody fuel loading (Stambaugh et al. 2007).

Conclusion

Empirical models depict temporal and spatial variability in litter and fire hazard within a seemingly homogeneous deciduous forest region. Regional litter depths are strongly influenced by time since leaffall which serves to increase fire hazard. Woody fuels appeared to be somewhat randomly distributed across the study region making them difficult to predict from ecological, plot, and social variables. In addition to future fire applications, the fuels dataset has other potentially important applications such as estimating above-ground carbon stocks or assessing changes in fuels that result from different forest management practices.

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