Understanding Ozark Forest Litter Variability Through a Synthesis of Accumulation Rates and Fire Events

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***Abstract**—Measuring success of fuels management is improved by understanding rates of litter accumulation and decay in relation to disturbance events. Despite the broad ecological importance of litter, little is known about the parameters of accumulation and decay rates in Ozark forests. Previously published estimates were used to derive accumulation rates and combined litter measurements, model estimates, and fire scar history data were used to derive a decay constant (k = 0.38). We used accumulation equations to demonstrate temporal changes in litter loading. For example, after a fire event that consumes nearly 100 percent of the litter, about 50 percent of the litter accumulation equilibrium is reached within 2 years, 75 percent within 4 years, and the equilibrium (99 percent accumulation) after approximately 12 years. These results can be used to determine the appropriate prescribed burning intervals for a desired fire severity. For example, fire history data show that the percentage of trees scarred, a surrogate for fire severity, is influenced by the length of historic fire intervals (i.e., amount of litter accumulated). This information will be incorporated into regional fire risk assessments and can be used as a basic knowledge of litter dynamics for both fire management planning and forest ecosystem understanding.*

Introduction

The Ozark Highlands lacks a general synthesis of the rate of litter accumulation and temporal variability of litter following fire events. Information on the temporal variability of fuels is needed by fire and forest managers in order to measure the success of management activities. In addition, information on litter accumulation is critical for modeling and monitoring of fuel loading and fire effects. This information is regionally specific and depends on the balance between rates of litter accumulation and decomposition (Olson 1963). Litter accumulation rates are controlled by vegetation type, decomposition rate, ecosystem productivity, and their interrelationships. Litter accumulation rates can be difficult to predict because of the high variability imposed by changes in species, tissues, vertical structure of vegetation, elevation, site, and time of year (Gosz and others 1972). Litter decays by leaching, physical weathering, faunal activities, and microbial consumption. Microbial consumption is the primary mode of decay and it is a process controlled by physical and chemical litter properties and climatic conditions (Meentemeyer 1978, McClaugherty and others 1985). Meentemeyer (1978) presented a general equation for predicting average annual decomposition rates (k) from actual evapotranspiration (AET) and leaf lignin contents.

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In order to provide general information for the Ozark region we synthesized data from existing studies and produced a model for predicting litter accumulation. In this paper we 1) provide a regionally averaged fuel accumulation equation for use in estimating fuel loading and 2) describe the long-term variation in Ozark fuel loading with fire history data. The objectives of the paper are to develop a quantitative relationship between litter amounts and time, and use this relationship to examine the effects of fire management on the accumulation and decay of litter.

Methods

Ozark Litter Accumulation and Decay Estimates

Estimates of litter accumulation and decay parameters were derived from four sources: 1) previous published studies, 2) actual litter loading measurements, 3) empirical litter relationships, and 4) analysis of historic fire intervals and tree scarring.

Previous Studies—In a study in the northern Ozarks, Kucera (1959) ranked litter from oaks (*Quercus alba, Q. rubra, Q. marilandica*) as being most resistant to decay, followed by sugar maple (*Acer saccharum*), shagbark hickory (*Carya ovata*), and American elm (*Ulmus americana*). At the same location, Rochow (1974) estimated a litter decomposition rate (k) of 0.35 for oak-dominated forest. More recently, Ryu and others (2004) arrived at a similar estimate for a larger portion of the Missouri Ozarks using an ecosystem productivity model (PnET-II) (Aber and others 1995).

Litter Loading Measurements—Missouri Ozark region litter loading data was gathered for many forested sites and time periods (table 1). Litter was collected using clip plot methods, dried to a constant weight, and reported on a dry-weight basis. In addition, we gathered associated data, including collection date (pre- and post-burn), dates of fires, number of previous fires, and physical plot attributes (slope, aspect, vegetation type, overstory basal area, and stand density). Variability in litter sample weights likely occurred due to collection by different investigators, years of collection, and forest conditions. When possible, we only used measurements that excluded the zone of highly decomposed material commonly called the humus or duff layer. We estimated the litter decomposition rate (k) using the equation developed by Olson (1963), where the annual production of litter is divided by the standing crop litter. The mass of annual litter production was estimated using mean litter loading values collected one year after burning. Estimates of the average standing crop (steady-state level) of litter were derived from litter masses that had accumulated for >20 years and were based on multiple measurements taken from many Ozark sites (table 1).

Empirical Litter Relationships—We also estimated litter decomposition rates using Meentemeyer's (1978) general equation, which incorporates lignin contents and actual evapotranspiration (AET). Average litter lignin content for the important Ozark tree species was derived from previously published studies. Tree species included black oak (*Q. velutina*), scarlet oak (*Q. coccinea*), white oak (*Q. alba*), post oak (*Q. stellata*), and shortleaf pine (*Pinus echinata*) (table 2). No lignin contents were obtained for hickories (*Carya* spp.). Though there is likely high variability in decomposition rates due to

Table 1—Data on oven dry-weights of litter from 35 Ozark Highlands sites. Forest structure codes and site information are given at the bottom of the table.

Site	Forest structure	n	Basal area (ft^2/ac)	Years accumulation	Litter (tons/ac)	Litter (tonnes/ha)	Source
Knob Noster S.P.	1	5	80	2	3.02	1.11	authors
HaHa Tonka S.P.	1	5	58	2	3.12	1.14	authors
Meremac S.P.	1	7	108	3	2.50	0.92	authors
Taum Sauk Mnt S.P.	1	7	52	2	2.90	1.06	authors
Bennett Spring S.P.	1	4	66	1	2.56	0.94	authors
USFS - Mark Twain	1	7	51	1	2.71	0.99	authors
University Forest A1	1	2	55	1	2.18	0.80	authors
Baskett WMA A1	2	9	na	1	1.56	0.57	Rochow 1974
Stegall Mtn.	1	3	38	2	2.76	1.01	authors
Chilton Creek 2003	1	26	na	1	2.00	0.73	Hartman 2004
Chilton Creek 1998	1	26	na	>20	3.40	1.25	Hartman 2004
University Forest B1	1	na	na	1	1.64	0.60	Scowcroft 1965
University Forest B2	2	na	na	>20	5.45	2.00	Scowcroft 1965
University Forest C1	2	na	na	>20	3.88	1.42	Meier 1974
University Forest D1	2	na	na	>20	6.10	2.23	Paulsell 1957
Jerktail Mtn.1	2	18	96	>20	5.77	2.12	authors
Jerktail Mtn. 2	2	6	67	>20	4.17	1.53	authors
Powder Mill 1	2	10	82	>20	4.97	1.83	authors
Powder Mill 2	2	6	93	>20	4.00	1.47	authors
Akers1	2	14	99	>20	3.49	1.28	authors
Akers2	2	10	86	>20	3.88	1.42	authors
Alley Spring	2	6	93	>20	3.76	1.38	authors
Bay Creek 1	2	6	90	>20	3.84	1.41	authors
Bay Creek 2	2	6	73	>20	4.13	1.52	authors
Black River 1	2	15	na	>20	3.02	1.11	Kolaks 2004
Black River 2	2	15	na	>20	3.19	1.17	Kolaks 2004
Black River 3	2	15	na	>23	2.92	1.07	Kolaks 2004
Coot Mtn.	2	6	103	>20	3.23	1.19	authors
Williams Mtn.	2	6	90	>20	6.53	2.40	authors
Wildcat Mtn.	2	8	93	>20	4.29	1.57	authors
Baskett WMA B1	2	102	129	>20	6.52	2.39	authors
Goose Bay Hollow	2	8	110	>20	5.44	2.00	authors
Dent & Iron Co.'s [a]	2	na	na	>20	6.60	2.42	Loomis 1975
Sinkin Exp. Forest 1 [a]	2	na	na	>20	6.20	2.28	Loomis 1965
Sinkin Exp. Forest 2 [b]	2	na	30	>20	5.00	1.84	Crosby and Loomis 1968
Mean maximum accumulation (>20 years accumulation)					4.57	1.68	

forest structure: 1 = savanna/woodland, 2 = forest
na = not available
[a] contains organic matter
[b] shortleaf pine plantation

Table 2—Lignin contents of important Ozark forest species.

Species	Lignin content (%)	Source
Quercus velutina	25.70	Martin and Aber 1997, Aber (online data)
Quercus coccinea	18.70	Washburn and Arthur 2003
Pinus echinata [a]	25.50	Washburn and Arthur 2003
Quercus rubra [b]	23.43	Martin and Aber 1997
Quercus rubra and *Quercus alba*	23.48	Martinand Aber 1997
Mean	23.36	

[a] samples include *Pinus rigida* litter.
[b] samples include *Acer rubrum* litter.

variability among sites, climatic conditions (for example AET), and numerous vegetation assemblages, we utilized a multi-species average of lignin contents for the region since our aim is to develop a better general understanding of litter dynamics in the Ozarks. We obtained AET estimates for the Ozark Highlands region from the Global Hydrologic Archive and Analysis System (GHAAS). Data were 0.5 degree gridded average annual AET estimates given in millimeters per year (Vörösmarty and others 1998). We averaged long-term grid means for the Ozark region to get a mean regional AET value.

Historic Fire Intervals—Historic fire intervals were derived from four previously constructed published and unpublished fire scar history studies in the Ozarks. Study sites were located in Shannon County, Missouri and included Stegall Mountain (Guyette and Cutter 1997), Mill Hollow, MOFEP Site 3, and MOFEP Site 4 (Guyette and Dey 1997). Methods for sample collection, tree-ring crossdating, and fire scar dating can be found in several published studies (Guyette and others 2003, Stambaugh and others 2005). Site level fire scar chronologies were input to FHX2 software (Grissino-Mayer 2001) where fire intervals were calculated for each fire at each site as the number of years between fire events. Fire intervals were paired with the percentage of trees scarred in the fire year that ended each interval. The percentage of trees scarred was calculated as the number of sample trees scarred in a given year divided by the number of recorder sample trees in the same year. All data were pooled into a single dataset with 111 paired observations of fire intervals and percentage of trees scarred. Due to the changing characteristics of the anthropogenic fire regime (Guyette and others 2002), we only used data from the period A.D. 1700 to 1850 in the analysis. This period was selected because it is well replicated (9-20 recorder trees at any given year) at all sites and because there exists high variation in the length of fire intervals. We used non-linear regression (exponential equation) to describe the variability in the percentage of trees scarred from fire intervals. We assumed that the variation in percentage of trees scarred is related to fuel accumulation. Based on this assumption, an exponential function should approximate the litter accumulation rate and the exponential term of the regression model would be an estimate of litter decomposition rate (*k*).

Temporal Litter Variability Model

The mass loss of litter as a function of time is generally expressed as an exponential decay model (Bärlocher 2005, Olson 1963). The temporal litter variability for Ozark forests was described using an exponential decay function:

$$X_t = X_0 * e^{-kt},$$

where X_t is the amount of litter remaining after time t, X_0 is the initial quantity of litter, and t is time of accumulation. The estimated rate of litter decomposition ($k = 0.38$) was a mean derived from four different procedures (table 3). The mean standing crop of litter (4.57 tons/acre, see results on next page) was used to define maximum mass accumulation. We used the exponential decay function to describe the rate of accumulation of litter and the time required to reach maximum litter accumulation. Additionally, the equation was applied to historic fire event data from four Ozark fire scar history sites (Stegall Mountain, Mill Hollow, MOFEP Site 3, MOFEP Site 4) in order to reconstruct past temporal variability in litter loading. Using fire scar chronologies, the model was initiated at the first year of record. Fire event

Table 3—Litter decomposition rates (*k*) from the Missouri Ozark Highlands.

Method	*k*	Source
Litter loading measurements	0.46	this paper
Climate/leaf lignin model	0.64*	this paper
Historic fire intervals	0.34	this paper
Litter loading measurements	0.35	Rochow 1974
Climate/leaf lignin model	0.35	Ryu and others 2004
Mean	0.38	

*not used to calculate mean

years were used to reset the litter accumulation model to zero. Accumulation following fire events assumed 100 percent fuel consumption and a constant weight of annual litterfall.

Results

Ozark Litter Accumulation and Decay Estimates

Litter Loading Measurements—The mean mass of annual litter production was 2.11 tons/acre (n = 6, s.d. = 0.47) or 0.77 tonnes/hectare. The mean standing crop of litter was 4.57 tons/acre (n = 24, s.d. = 1.22) or 1.68 tonnes/hectare. Based on the ratio of mean annual production of litter to the mean standing crop, the estimated litter decomposition rate (*k*) was 0.46.

Empirical Litter Relationships—Average percent lignin contents of litter for the important Ozark overstory forest tree species (table 2) was 22.63%. AET values ranged from 675 to 760 mm/yr and the mean was 712 mm/yr. Based on Meentemeyer's (1978) equation the estimated litter decomposition rate (*k*) ranged from 0.59 to 0.69.

Historic Fire Intervals—The relationship between the percentage of trees scarred in a fire event and the preceding fire interval (years since last fire) was established using the non-linear equation:

$$\text{percent trees scarred} = 13.8 + 7.72\,(\ln[\text{fire interval}]),$$

where the fire interval is years since last fire event (model $r^2 = 0.21$, intercept and variables significant $p<0.0001$, n = 111). Although the fire-free interval model explained only about one-fifth of the variance, the model and variables were highly significant. The form of the equation resulted in an exponential term (litter decomposition rate (*k*)) of 0.34.

Temporal Litter Variability Model

The temporal litter variability for Ozark forests was described using an exponential decay equation and is presented in terms of percent accumulation (eq. 1) and mass accumulation (eq. 2).

$$\text{Percent accumulation} = 100 - (100e^{-0.38t}) \qquad \text{(eq. 1)},$$

$$\text{Mass accumulation} = 4.57 - (4.57e^{-0.38t}) \qquad \text{(eq. 2)},$$

where t is the years of litter accumulation. The equation predicts that litter accumulates to 25 percent, 50 percent, and 75 percent of maximum accumulation at approximately 1 year, 2 years, and 4 years, respectively (fig. 1). An equilibrium accumulation (99 percent) is reached at approximately 12 years. In terms of mass accumulation, roughly one ton of litter per acre is accumulated per year up to 3 years post-fire (fig. 1).

The litter accumulation function showed important differences in litter accumulation with burning frequency (fig. 2). For example, annual burning allows a maximum of 32 percent of the total litter to accumulate. A burning frequency of 5 years allows a maximum of 85 percent of the total litter to accumulate, while a burning frequency of 10 years allows a maximum of 97 percent of the total litter to accumulate. In terms of litter loading, the difference between annual and 5-year burning frequency is over two times greater than the difference between 5-year and 10-year burning frequencies.

The effects of variable burning frequencies were further exhibited by a reconstruction of long-term Ozark litter loading (fig. 3). The long-term variation in historic fuel loading is striking and a result of frequent anthropogenic ignitions. Prior to EuroAmerican settlement (pre-1800), fuel loading was both spatially (between sites) and temporally variable. Comparisons between sites show that Stegall Mountain has undergone conditions of continuous burning and rapid fuel replenishment. Mill Hollow and MOFEP Sites 3 and 4 underwent prolonged frequent fires (1-3 years) that lasted most of the 19th century and had a long-term effect on minimizing fuel loading. Mean fuel loading of the four sites was 2.91 tons/acre prior to 1800 and 1.45 tons/acre from 1800-1900. Since about 1930 to 1940, the effects of fire suppression has resulted in maximum litter loading and lowered temporal litter variability. An exception is Stegall Mountain, where prescribed burning management has been in practice since about 1980.

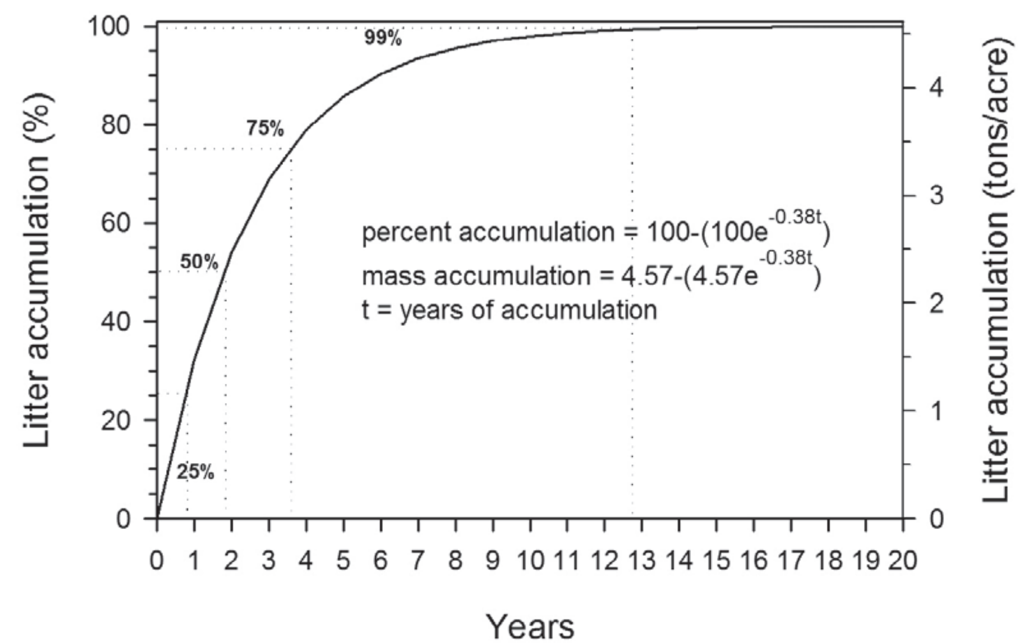

Figure 1—Plot illustrating a litter accumulation function in terms of percent of maximum and mass for forests of the Ozark Highlands, Missouri. The decomposition constant (*k*) was based on the mean from multiple sources and methods (table 3).

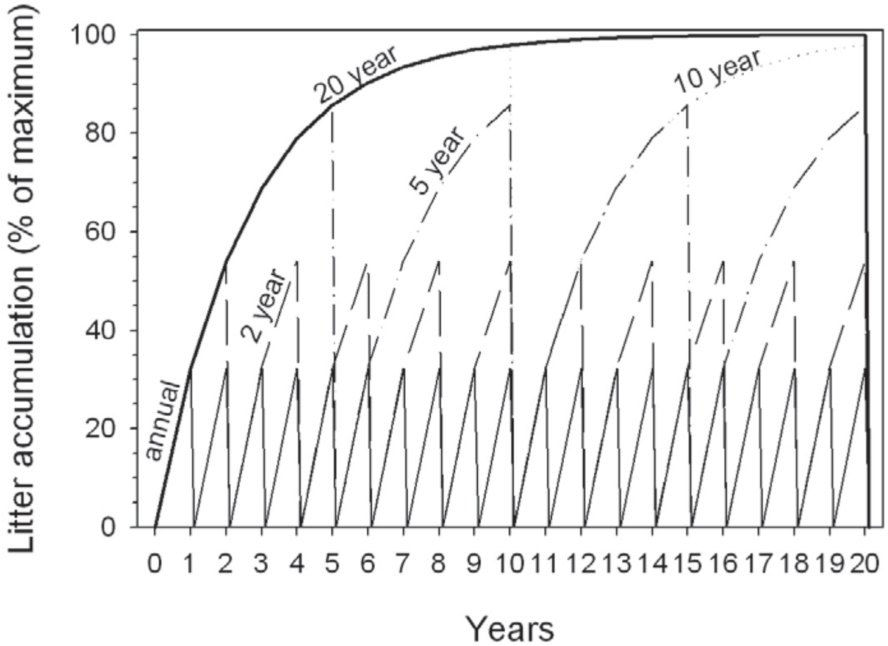

Figure 2—Litter accumulation dynamics with litter removed by fire (or other means) at different but regular intervals. Given here are litter accumulation patterns for annual fire intervals (solid fine line), 2-year fire intervals (short dashed line), 5-year fire intervals (dot dashed line), and a single 20-year interval (solid bold line).

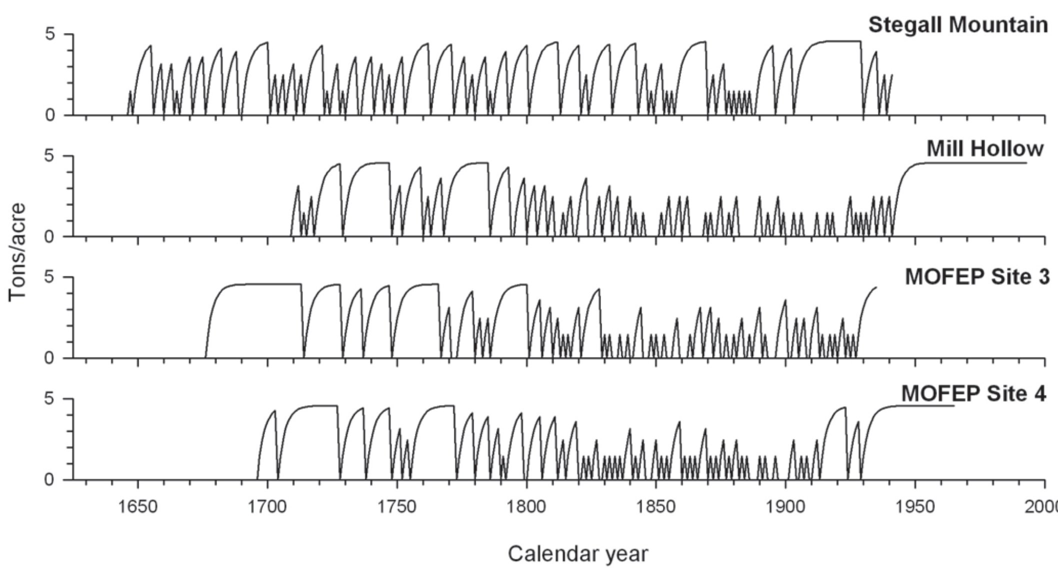

Figure 3—Litter loading reconstructions for four forest sites in the Ozark Highlands, Missouri. Reconstructions are based on fire scar history data and a litter mass accumulation function (fig. 1). Site reconstructions begin and end at different calendar years based on the period of fire scar chronology records.

Discussion

Fire suppression policies of the past 75+ years have altered Ozark forest ecosystems, often in ways that are not fully understood at this point in time. From fire scar studies, we know that much of the Ozarks landscape burned relatively frequently (8-15 years) for at least 200 years prior to Euro-American settlement. The natural communities that developed during that time are now changing, and restoration efforts often include the reintroduction of fire, despite a lack of quantitative information on how fire might behave under the conditions resulting from years of fire suppression. One of the many ways in which fire suppression has affected Ozark forests is by altering the nature of fuels at the forest floor, though there has not previously been a way to quantify these changes. In this paper, we present a litter accumulation model specific to the Ozark region, which we hope will improve our general understanding of the temporal variability in litter accumulation and our ability to manage fuels effectively in the Ozarks. The litter accumulation equations provide managers and scientists with a standard of expected fuel loading, the potential effects of different burning frequencies on fuel accumulation and loading, and estimates of the historic variability in fuel loading at four Ozark sites.

Estimates of temporal changes in fuel depend primarily on the litter decomposition rate (k) and level of maximum litter accumulation. The best estimates of litter decay and accumulation in the Ozarks were based on litter loading measurements and the historic fire record. We chose not to include the value of k derived from mean annual AET and lignin contents as the estimate was extremely high ($k = 0.64$). Though litter decomposition rates differ from year to year due to changing conditions (for example climate, species, forest density), we felt that the value was a gross overestimate and outside of a plausible range of rates (Ryu and others 2004). The increased rate of decomposition of mixed-species litter (Gartner and Cardon 2004) was unaccounted for, and may be one important reason why Meentemeyer's equation yielded a decay constant much higher than other estimates.

The rapid accumulation of litter following disturbance events likely leads to large differences in burn coverage and fire behavior between fire frequencies of 1, 2, and 3 years. To illustrate this point Behave Plus 3.0.1, fire behavior prediction software, was used to estimate the different fire rates of spread and flame lengths between fuel accumulation rates at 1, 2, and 3 years (table 4). All else equal, fires occurring at 10-year intervals versus 20-year or longer intervals may not differ significantly in behavior or severity (percent trees scarred)

Table 4—Behave Plus prediction of fire behavior using litter accumulation rates from this study. Behave Plus was run using fuel model 9 and 1 hour fuel loading was adjusted according to accumulation rates.

Litter Accumulation Rate	Midflame Windspeed (mph)	Slope (%)	1hr % Moisture Content	10hr % Moisture Content	Rate of Spread (chains/hr)	Flame Length (ft)
1 yr (25% max)	10	5	5	7	24.8	3.3
2 yr (50% max)	10	5	5	7	29.4	4.5
3 yr (65% max)	10	5	5	7	30.1	4.9
10 yr (97% max)	10	5	5	7	29.5	5.3
20 yr (100% max)	10	5	5	7	29.6	5.3

because the level of litter accumulation is similar (table 4). One important factor in surface fire behavior is litter moisture content which can be highly variable by aspect and drought condition (Stambaugh and others, in press). Litter profiles can also be highly variable with dry litter on the surface covering a relatively moist "mat" of partially decomposed but identifiable leaves of the previous few growing seasons (Crosby 1961, Loomis 1975). Furthermore, although fuel loading following 10 and 20 years of accumulation may be marginal, important differences in the development and conditions of the underlying litter profile likely exist.

In addition to the quantification of accumulation and decay rates, the reconstruction of long-term litter loading under different fire regimes provides a unique perspective for fuels management. Although difficult to substantiate, frequent burning during the 19th century may have altered the nature of Ozark fuels by increasing herbaceous and grass vegetation, possibly leading to even lower fuel loading (for example tons/acre) than reconstructed (fig. 3). Frequent and long-term burning likely led to a transition in the dominant litter type from forest leaf litter to herbaceous grass and forb litter, which possibly resulted in increased decomposition rates and decreased total litter loading. In the southeastern Missouri Ozarks, Godsey (1988) found that both annual and periodic and annual burning of an oak-hickory forest after 36 years resulted in an increased abundance of grasses, forbs, and legumes that only comprised about 0.02 tons/acre. Additionally, Hector and others (2000) discussed the differences in decomposition between plant functional groups (legumes, grasses, herbs) and showed increasing decomposition rates with decreasing litter carbon to nitrogen ratios. The conditions conducive to high litter loading potential are most likely found where forest floors are dominated by leaf litter and have been subject to fire suppression for more than 12 years. Much of the forested area of Missouri has had no fire disturbance since the mid-20th century, which has resulted in relatively high litter loading and reduced variability in litter loading compared to the previous 200+ years.

The accumulation of organic litter on forest floors has implications for many processes which involve soils, litter invertebrates, floral diversity, hydrology, and carbon cycling. Furthermore, the effects of historically frequent fire and reduced litter, as well as current and future effects, are poorly understood. Several studies have commented on the slow recovery of endophage populations and activity following burning (Crossley and others 1998). Auten (1934) and Meier (1974) found that burned Ozark sites had significant reduction in water infiltration compared to unburned sites. Studying the same Ozark experimental burn plots, Scowcroft (1965) speculated that prolonged, frequent burning eventually led to decreased soil productivity. Frequent fire also results in decreased fuel connectivity, particularly as canopy trees are killed and inputs of litter are reduced (Miller and Urban 2000). These represent only a few of the myriad of ways that frequent fire may impact forest processes, and highlight the value of continued research into the dynamics of fire frequency and severity and the subsequent impact on organic litter accumulation.

Prescribed burning management is faced with multiple challenges in the Ozark region. Few studies have been conducted to investigate the effects of fire on multiple ecosystem components. Meanwhile, previously fire-maintained communities and species are decreasing in area and abundance, and require fire disturbance to persist. Even with relatively general information about litter decay and accumulation, decisions about forest management and prescribed burning activities are better informed. For example, successful regeneration of shortleaf pine, a species of restoration concern in the Ozarks, could be greatly enhanced through better understanding of the rate of litter accumulation, which often precludes seedling establishment. Also, burning prescriptions for areas being managed for multiple resources can be tailored to achieve an optimal level of fuel loading and desired fire behavior.

Though based on regionally specific data from the Ozarks, the litter accumulation and decay estimates presented here are generalized and do not take into account interannual variability due to variable fire effects (for example partial litter consumption), climate, litter production, litter chemistry, and other influencing factors. Despite these limitations, the approach to understanding long-term litter variability is new and applicable to other locations. Many improvements to this approach are attainable, including: the incorporation of variability in fuel accumulation and decomposition between leaf fall events; taking changing climate into account; addressing differences in species and vegetation densities; and, addressing differences in modern and historic fire conditions (for example fuel consumption, fire severity). The estimates and equations provide a context for fuels management under current conditions, facilitate a new understanding of historic fire regimes, and provide the foundation for a more refined understanding of the fuel-fire interaction.

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