Curr Forestry Rep (2015) 1:91–99
DOI 10.1007/s40725-015-0012-x

FIRE SCIENCE AND MANAGEMENT (M ALEXANDER, SECTION EDITOR)

The Flammability of Forest and Woodland Litter: a Synthesis

J. Morgan Varner[1] · Jeffrey M. Kane[2] · Jesse K. Kreye[3] · Eamon Engber[4]

Published online: 3 April 2015

Abstract Fire behavior and effects in forests and woodlands are influenced by surface fuels and senesced leaf litter in particular. We have known that species exhibit differential flammability for some time, but isolated efforts have often attributed differences to disparate mechanisms. Recent research has expanded the diversity of species evaluated, clarified patterns at the fuelbed level, and provided evidence that the physical and chemical traits of litter or fuelbeds drive flammability. To date, little effort has focused on uniting methods, clarifying the awkward terminology, or, perhaps most importantly, comparing laboratory findings to field observations of fire behavior. Here, we review recent literature and synthesize findings on what we know about the flammability of litter and propose future research directions.

This article is part of the Topical Collection on *Fire Science and Management*

✉ J. Morgan Varner
mvarner@vt.edu

Jeffrey M. Kane
jkane@humboldt.edu

Jesse K. Kreye
jesse.kreye@msstate.edu

Eamon Engber
eamon_engber@nps.gov

1 Department of Forest Resources and Environmental Conservation, Virginia Tech, 310 West Campus Drive, MC 0324, Blacksburg, VA 24061, USA

2 Wildland Fire Laboratory, Department of Forestry & Wildland Resources, Humboldt State University, One Harpst Street, Arcata, CA 95521, USA

3 Department of Forestry, Forest & Wildlife Research Center, Mississippi State University, Miss State, MS 39762, USA

4 Redwood National Park, 121200 Highway 101, Orick, CA 95555, USA

Keywords Fire behavior · Fire ecology · Fuels · Methods · Plant species traits · Scaling

Introduction

Forest and woodland fire behavior is a complex result of topography, weather, and fuels [1]. Topography remains fairly stable over time, while weather is capable of changing instantaneously. The moisture content of fuel can change dynamically with weather, but the composition and structure of fuels are more stable. Fuel composition and structure fluctuate seasonally [2] and over longer time periods as vegetation shifts occur as a result of disturbance, succession, or ecosystem migration [3, 4, 5••]. Surface fuels in forests and woodlands consist of senesced leaves, branch and stem woody debris from trees and shrubs, and living and dead grasses, forbs, and shrubs [6]. Due to their ubiquity and mass, a major driver of surface fire regimes is senesced leaves or "litter" [3]. The differences in species composition, decay, arrangement, and moisture all interact to dictate ignition, fireline intensity, rate of fire spread, and consumption of fuels. These characteristics of fire behavior are collectively termed "flammability" or the ability of a fuel to burn [3, 7, 8].

In spite of the importance of litter flammability, no far-reaching syntheses or critical reviews exist on this topic. Gill and Zylstra [3] review the general topic of flammability with a focus on Australian ecosystems and their management, following on an earlier examination of the topic and the elusiveness of definitions [9]. White and Zipperer [10] review how flammability characteristics are examined and discuss how variation in the flammability of landscaping plants mitigates fire hazard in the wildland-urban interface. Pausas and Moreira [11•] provide justification for studying flammability and review the topic and some emergent findings.

Observations that species differ in flammability have been repeatedly observed [e.g., 4, 12, 13]. While some have proposed that these differences reflect evolutionary adaptations to fire regimes [14–16], others have criticized this idea by stating the possibility of exaptations [17, 18]. Clear evidence that litter flammability is an evolutionary adaptation to fire in some species remains difficult to prove; regardless, understanding the patterns and mechanisms of litter flammability has important relevance to predicting fire behavior and ecological impacts in fire-prone ecosystems [11•].

In this synthesis, we review the literature on leaf litter flammability and recent advances. A substantial amount of research has focused on this topic, ranging from fire hazard prediction to evolutionary relationships. In spite of the recent attention, much about litter flammability remains unknown. The intent of this review is to synthesize the existing research to (1) review the evidence for mechanistic drivers of litter flammability, (2) compare and critique methodologies and measurements used to assess litter flammability, (3) evaluate the needs and impediments to scaling up laboratory findings to the field level, (4) revisit relevant concepts and components of litter flammability, and (5) provide areas for future research. We hope this synthesis spawns future research in these knowledge gaps.

Flammability—a Definition

Flammability generally refers to the capacity of wildland fuels to ignite and combust. While simple in concept, the problem of adequately defining flammability has long been recognized [19]. Anderson [7] proposed that flammability includes three components: "ignitability," the delay on ignition; "sustainability," the duration of combustion; and "combustibility," the mass loss rate. Martin et al. [8] added a fourth facet: "consumability," the proportion of fuel consumed by fire. These lab-based components are linked to field fire behavior and effects metrics of probability of ignition and rate of spread (ignitability), fireline intensity (combustibility), flame front residence time (sustainability), and fuel consumption (consumability; [3]; Table 1). However, a meaningful and consistent linkage between the various components of flammability and field-based observations and measurements of fire behavior is generally lacking. Here, we use evidence from recent research to revisit these basic tenets of flammability.

Determining Flammability: Methods

Flammability research has relied on a variety of research spanning ex situ leaf-level experiments to in situ fuelbed research. The presumed overreliance on laboratory-based research on individual species [20] is the result of the difficulty in measuring flammability in wildland fires. Wildlands are composed of diverse fuels and variation in weather and topography. Isolating the effects of individual species and proximate mechanisms for observed variation is difficult, as acknowledged in a variety of field settings [e.g., 21, 22]. Lab-based studies can provide a means to isolate potential mechanisms by burning and comparing dominant species of varying characteristics [11•] and then building complexity over time in lab settings and through comparisons with field experiments. The overwhelming focus has been on lab-based studies; our ability to link these phenomena to field-based observations and measurements remains a challenge.

Laboratory Flammability

Litter flammability research has primarily concentrated on single species in a laboratory setting. Early flammability research focused overwhelmingly on ignition delay [7, 23] and on fuel chemical properties such as energy or heat content [24], the content of silica or other minerals that suppress ignition or dampen intensity [25, 26], or generated combustible gases [24]. Much of this research was aimed at individual leaves or altered litter samples (e.g., calorimetry or combustible gas analysis). Notable exceptions to these shortcomings include early research on the effects of moisture on ignitability [27] and litter fuelbeds from a variety of species [14].

Laboratory methods focus on deriving metrics of flammability, typically via measurement of individual species fuelbeds. Ignitability, often measured using a pilot heat source such as a muffle furnace, is typically measured with individual leaves or via firebrand ignition of intact fuelbeds [28]. Ignitability is a binary response variable making its analysis complicated. Flaming has been measured in laboratory burning experiments via measuring flame dimensions (flame height, as a measure of intensity in a wind- and slope-free environment; flame depth; and angle) and flaming duration. Smoldering, or glowing combustion, is measured primarily by its duration of glowing. Residual ash is measured as a metric of fuel consumption. Other ancillary metrics include mass loss rates [29], rates of spread [13, 30••], and mixtures of temperatures above the fuelbed (as measured with thermocouples [e.g., 31]).

The metrics evaluated by flammability studies are generally consistent, but comparison across methods is challenging. Few studies follow consistent methods, a considerable impediment to comparing results between or among studies. Even when studies follow a consistent method, there are cases of intraspecific differences. For example, in two separate experiments with litter of *Pinus ponderosa*, Fonda [12, 32] found different flammability values. Plausible explanations for these differences could be (i) that species' flammability differs across a wide native range due to phenotypic plasticity and genetic diversity or (ii) studies lack repeatability. The latter is more worrying, but anecdotal results from several species

Table 1 Overlapping concepts and fire measurements used to describe and quantify flammability

Phases of combustion	Components of flammability	Laboratory measurements	Field measurements
Pre-ignition	Ignitability	Time to ignition	Probability of ignition
Dehydration		Ignition temperature	Fuelbed receptivity
Oxidation			
Pyrolysis			
Ignition			Probability of spread
Combustion	Sustainability	Flame length	Flame length
Flaming	Combustibility	Rate of spread	Rate of spread
Smoldering		Flaming duration	Residence time
		Smoldering duration	Flame temperature
		Mass loss rate	Fireline intensity
		Flame temperature	
		Fireline intensity	
Extinction	Consumability	Mass loss	Fuel consumption

suggest that species do indeed have repeatability. However, we are not aware of a thoughtful investigation of this potential methodological issue. Beyond these potential limitations, there may be other measures of flammability that go unrecognized. Understanding how to quantify a multivariate response such as flammability is a challenge, as are many areas of fire metrology [33].

Patterns of Differential Flammability

Building on Mutch's [14] initial findings that species differ in litter flammability, many subsequent studies have expanded the number of species examined and several broad patterns have emerged. Recent important results include research from North America [2, 4, 5••, 12, 30••, 34, 35••], Australia [36–39], Europe [13, 28, 31, 40–43], and South America [44]. The patterns differed by study, but a consistent finding is that species differ in their flammability metrics. More remarkable is the detection of differences between species typically understood to be analogs of one another—e.g., *Pinus ponderosa* and *Pinus jeffreyi* in dry western North American forests and *Pinus palustris* and *Pinus elliottii* var. *densa* in Floridian woodlands [12]. Further, the magnitude of differences between species was also marked, with order-of-magnitude differences in intensity across species within similar landscapes.

Drivers of Flammability

Beyond the patterns across species, recent research has delved into the mechanisms of flammability—why some species burn readily and others seemingly resist ignition or dampen fire intensity. Following on early work, Scarff and Westoby [36] found that differences in leaf size, and subsequent effects on fuelbed bulk density, were a primary driver of flammability. Larger leaves created open, low-bulk-density fuelbeds that allowed greater airflow and burned more rapidly. Similar results have been found in western North America conifers [34], oaks in the western and southeastern USA [4, 35••], and temperate eastern Australian species [38]. The emergent finding of these studies is that leaf traits matter: long, curling leaves burn with greater intensity and rapid duration and consume more fuel [38, 39]. Species with greater lobing (or dissection) and a deciduous leaf habit (as in many *Quercus* species) accentuate these patterns [4, 35••]. Further, characteristics of the fuelbeds matter: litter that builds low-bulk-density fuelbeds (large or curled leaves) burn with greater intensity and rapid duration and consume more fuel (Fig. 1).

In spite of the evidence that physical traits influence flammability, a dominant paradigm is that leaf chemistry is the (or among the) dominant driver of flammability. Few studies, however, thoroughly evaluate potential biochemical mechanisms. Early research focused on individual chemical components, particularly mineral content and caloric content, as likely mechanisms for interspecific differences. Calorimetry research [10, 45] only touches on potential heating and removes otherwise important leaf physical traits in the process. A provocative recent exception [13] evaluated terpene concentrations on flammability of six Mediterranean species. Terpene fraction was broadly related to flammability, but individual terpenes were tightly linked to flammability across species. In particular, the sesquiterpenes α-humulene, β-caryophyllene, and caryophyllene oxide increased aspects of flammability more than the monoterpenes α-pinene and β-pinene. These results and the general conclusions of early mineral content research suggest that litter chemistry clearly plays a role (Fig. 1), but pose further questions about how chemical properties might interact with physical leaf and

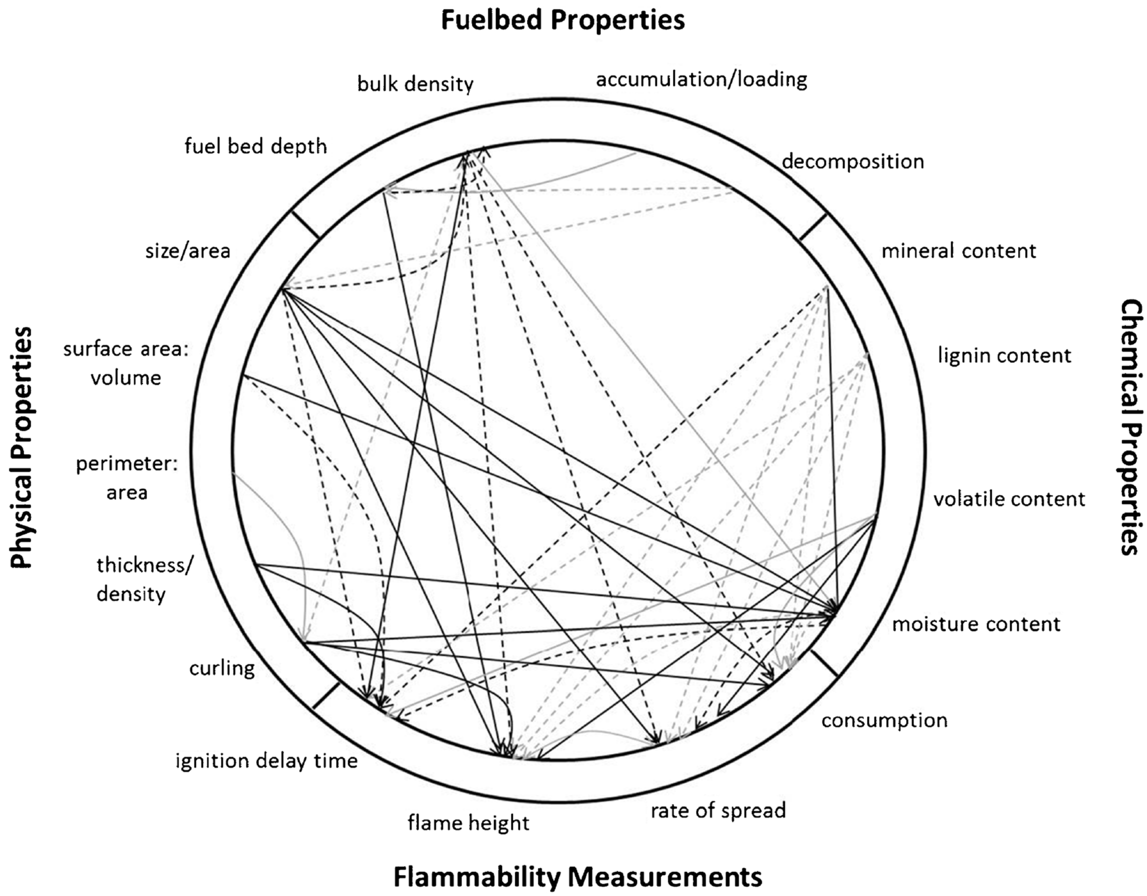

Fig. 1 Relationships among physical properties, chemical properties, fuelbed properties, and flammability measurements. *Black lines* represent relationships based on published lab-based studies of litter flammability, and *gray lines* represent possible relationship based on other studies. *Solid lines* refer to positive relationships and *dashed lines* refer to negative relationships

fuelbed properties or how litter decomposition might influence litter chemistry.

Fuel moisture is a major determinant of flammability across many ecosystems. Laboratory flammability experiments overwhelmingly rely on "dry flammability" that is, species are burned under very low moisture contents (<5 % oven-dry weight basis). An argument made for this method is that it approximates "wildfire conditions," and in many seasonally dry ecosystems (e.g., western North America, Mediterranean climates worldwide), this dry litter treatment may be appropriate. Litter gains and loses moisture differentially across species [5••, 46•]. Litter ignitability varies with moisture content [37, 47], but few studies evaluate variations in moisture with broader metrics of flammability. In pilot sampling of four North American conifers, it was found that species changed rank order in flammability based on time of drying (Cigan, Varner, and Engber *unpublished manuscript*). Differential drying rates among species resulted in species that burned with greater intensity when dry but burned less intense than expected during drying. Similarly, Mola et al. [5••] found that species were distinct when considering both drying rates and burning characteristics. Future research should focus on incorporating moisture dynamics with other aspects of flammability to better understand the complexity inherent in litter fuels.

We lack research that evaluates the multiple plausible variables that drive litter flammability. Research that evaluates litter flammability using physical and biochemical traits across a diversity of taxa is sorely needed. One method to assess the proximal mechanisms of litter flammability is through better integration of emergent research and databases on plant traits. Flammability research uses many of the same morphological, anatomical, biochemical, and phenological characteristics suggested for trait-based ecology [sensu 48]. Flammability researchers should use larger plant trait databases (e.g., "TRY"; [48]) or plan research in a synthetic manner that enables similar generalizable results. A species-by-species approach is not only time-consuming but, due to factors discussed above, may blur patterns that may be generalizable to broader suites of species and fuels.

Understanding the differential flammability of species research provides an ecological context that can inform management of fire-prone ecosystems. For example, in southeastern USA *Pinus-Quercus* woodlands, the dominant management paradigm is that *Quercus* species are invaders and should be diminished or removed because they impede fire spread and diminish intensity thereby compromising other silvicultural, plant biodiversity, and imperiled vertebrate conservation management objectives. Kane et al. [4] compared the flammability of eight oaks and determined that several impeded fire, while the other oaks burned with comparable flammability to the highly flammable and co-occurring *P. palustris*. Similarly, in ravines of northern Florida, Mola et al. [5••] evaluated the loss of two poorly flammable rare conifers (*Torreya taxifolia* and *Taxus floridana*) and the potential consequences to changes in community flammability. They found that the loss of these species and the subsequent increases in more flammable tree species have resulted in greater community flammability, further imperiling the rare habitats. "Applied flammability" studies, such as these, have the potential to deepen our understanding of fire-vegetation relationships more broadly [49, 50].

Reconsidering the Elements of Flammability

When exposed to an ignition source, litter fuels undergo dehydration, pyrolysis, ignition, combustion, and extinction [3, 7]. The elements of flammability have more or less tracked these phases, with greater attention to active flaming and smoldering behavior. Little attention has been placed on pre-ignition phenomena, as highlighted in the lack of research tying drying to burning [51] and to the scant attention to litter ignition in general. The focus on flaming is straightforward as visible flames can be quantified in a variety of ways and have direct links to heat release and fire effects. In spite of this, few flammability experiments have characterized flame characteristics beyond coarse measures of flame height, depth, or duration of visible flames. Work on mass loss rates in woody fuels [29] offers a path for understanding heat release rates. Other measures of radiation and convection in the flaming phase should be pursued. Similarly, measuring smoldering durations is overly simplistic. For instance, we are aware of no flammability research that measures smoldering once it begins; instead, studies typically note the initiation of smoldering once the fuelbed ceases flaming. Smoldering also has long "tails, " that is, isolated patches of fuel (often isolated leaves) smolder long after the fuelbeds cease glowing [e.g., 4]. Using these likely outliers in analyses may mask species differences or blur our understanding of flammability more generally. Consumability is more straightforward, yet there are shortcomings with its measurement as well. Few studies have separated the residual unburned fuels from ash, and we are unaware of any research that has characterized the ash remnants. These subtleties may have importance in that incomplete combustion may portend vast differences in fire effects (i.e., surface water flow or nutrient availability). Clearly, these are oversights, but it also highlights how simple our approach to measuring flammability has been.

Beyond the shortcomings of measurement, the terminology used to characterize the elements of flammability fails to clarify the phenomenon. Whether Anderson's [7] original attempt at a definition, the additions by Martin et al. [8] and others, ignitability, combustibility, sustainability, and consumability often do more to confuse rather than clarify. To illustrate, we argue that few would understand what it meant that one species' fuel was "more sustainable" than another. In addition, consumability (fuel consumption) is a first-order fire effect as opposed to how a fuelbed burns. To simplify, we propose that rather than create an analogous set of terms, researchers focus on the metric itself. For example, instead of declaring a species' sustainability, we should describe the duration of flaming and smoldering combustion separately. Each of these metrics (and other metrics measured in lab and field settings) has relevance across scales [11•].

Beyond the metrics of burning characteristics, there are shortcomings with the way we quantify flammability. As Gill and Zylstra [3] poignantly suggested: "the definitions have little meaning if values are correlated." We agree with this point, unless there are other emergent properties (e.g., fire effects) of these metrics. Several investigators have found that these "independent" metrics of flammability are highly correlated. For instance, fire intensity (as inferred from flame height or mass loss rates) has been tightly and negatively related to flaming duration (as should be expected) and often positively with fuel consumption [35••]. Smoldering duration is typically unrelated or poorly correlated with the other metrics. In multivariate analyses, these three (or four) metrics typically condense to two primary flaming and smoldering variables. These basic metrics and their interrelatedness suggest we have much to learn about the fundamentals of flammability.

Scaling From Leaves to Fuelbed Properties

Both leaf-level and fuelbed-level properties are of importance in the flammability of surface fuels. This would include factors such as fuelbed bulk density, packing ratio, porosity, and depth (Fig. 1). Fuelbed properties influence combustion [1]; however, the relationships between fuel particle and fuelbed properties and their combined effects on combustion are unclear. Long, dissected or curled leaves inflate fuelbeds [35••, 37, 40] and burn with greater vigor. Leaf variability across species may be important for forest floor flammability through their influence on fuelbed properties, although field evidence is lacking. Recent work [52•] evaluated the relationships between fuelbed permeability, fuelbed porosity, and leaf-level geometry of three pine species and evaluated their influences on flammability. Their laboratory findings showed the importance of leaf-level (pine needle) properties on ignition (leaf surface area:volume; "SA:V"), but independent of species, fuelbed permeability had an important influence on heat release rates during combustion. Permeability influences the flow of oxygen throughout the fuelbed, affecting combustion rates. Leaf properties may influence litter flammability directly, but leaf size and shape may also influence litter combustion indirectly through their effects on fuelbed-scale properties such as fuelbed depth, bulk density, porosity, or permeability. A provocative study by Ganteaume et al. [53•] illustrates that flammability results from "reconstructed" fuelbeds in lab burning experiments differ from "intact" or undisturbed litterbeds collected from the field. Lastly, fuel loading in laboratory flammability studies is typically controlled to evaluate species-specific or community-specific differences. Experiments typically use 15- to 300-g (dry weight) samples spread across 200- to 1000-cm^2 areas. In these approaches, the variability in fuel loading that can occur across short spatial scales [22] is eliminated. The constrained area and loading may obscure our ability to detect scale-dependent changes in flaming. How well fuels tested in the laboratory represent those found in the field is often untested, and how these factors interact in the combustion of litter remains unknown.

Beyond pure litter fuelbeds, woodland and forest surface fuels contain other components that determine community flammability. At its simplest, senesced foliage falls and intermixes with previously fallen tree litter (either from the same or different species) and herbaceous fuels. Herbs (forbs and especially graminoids) not only add to the surface fuelbed, but they also "perch" fallen leaves [35••]. Understory shrubs and small trees act similarly; these "draped fuels" are often important in surface fires and local areas of shrub or tree torching [6]. Small and large woody fuels and fallen pine cones add to this complexity [54]. Litter flammability research has largely ignored these potential interactive structures. The same absence of research on species-level differences and complications due to decay that hinder litter research has the potential to confound other elements of the surface fuels.

Fire Environment: Wind and Topography Effects

Few flammability studies incorporate wind [but see 37, 41, 42, 55]. The presence of wind decreased ignitability at the fuelbed surface but aided ignition when it occurred within the fuelbed [37]. Flammability studies conducted in no-wind conditions successfully evaluate species-specific variability in flammability, but the extent these differences occur in the field under varying wind conditions has yet to be evaluated.

In spite of its importance, few flammability studies have considered variation in slope steepness on fire behavior. Dupuy [56] evaluated the effects of fuel load and slope on rates of fire spread and mass loss during laboratory burning of litter collected from *Pinus pinaster* and *Pinus halepensis* stands in southern France. Spread rates and mass loss were related to slope (−30° to 20°) in a parabolic shape, but these relationships differed not only with fuel load but also between species. Liu et al. [57] burned *Pinus sylvestris* var. *mongolica* litter and found that with increasing slopes, rates of spread and mass loss increased, but consumption efficiency (proportion of mass consumed during flaming) diminished; all three relationships were nonlinear. These experiments underscore general patterns (i.e., slope steepness matters) but collectively fail to inform our broader understanding of litter flammability.

Mixed Species: Evidence for Synergistic Effects?

Most flammability studies focus on single-species fuelbeds. The effect of two or more species (as is typical in many forest and woodland types) on flammability has been less thoroughly examined. Mixed-species litterbeds are complex and offer potential outcomes that are not apparent when burning single species in isolation. Mixing species could result in (i) synergistic (or "non-additive") responses such as increased flame dimensions or abbreviated durations, (ii) dampened responses where flames are diminished and durations extended, or (iii) no effect, where the outcome of mixing species is simply the arithmetic mean of the component species.

Results to date suggest that litter flammability of mixed-species forests will be driven by the larger or longer-leaved species. In the only two studies we are aware of [30••, 58•], mixed-litter burns resulted in synergistic effects on flammability driven by the presence of more flammable species. We have data (Varner, Kuljian, and Kreye *in revision*) based on mixed-species litterbeds from northwestern California, suggesting that when poorly flammable *Pseudotsuga menziesii* was added to other species, dampened flammability resulted. These contradictory findings highlight the need to more fully investigate the influence of mixed species on flammability.

The future of laboratory-based flammability research faces some hurdles. Our synthesis underscores the need to better incorporate fire environment and fuelbed variation into flammability research. Including variation in topography (i.e., slope steepness) and winds is a straightforward path, although the potential variations and interactions between these two are complicated. The more problematic issue is fuelbed diversity effects. Mixed species, moisture dynamics, the effects of litter decay, and fuelbed structure (particularly incorporating herbaceous and woody fuels) all deserve more attention. Future flammability research should also focus on linking patterns of differences to proximate mechanisms. As illustrated, there is a lack of research that simultaneously evaluates physical and biochemical traits, in spite of the long-held opinion that both of these are important [59] and perhaps interacting. Lastly, improvements should focus on determining comprehensive litter flammability measurements and using consistent, repeatable methodology. With these leaps in methods and analysis, the links between field and laboratory results will become clearer.

Scaling Laboratory Results to Wildland Fires

Arguably, the biggest gap in our understanding of litter flammability is how laboratory findings scale up to wildland fires [20]. In the small number of studies that use similar species in lab and field studies, field evidence supports lab results (e.g., [4] in the lab; [60] in the field). The goal of flammability research should be to appreciate, not eliminate, the diversity of factors that control fire behavior. Research approaches that alter (or eliminate as in calorimetry) leaf physical or biochemical traits (via excessive or high-temperature drying) should be cautiously interpreted. As these traits inform mechanisms, they can be useful; as they blur patterns in the field, they may do more harm than good [20]. Studies that approximate field composition (via species mixtures) and structure (whether via "intact" sampling or careful fuelbed reconstructions) should be encouraged. Simply stated, the relevance of litter flammability research to our global understanding of fire behavior and first-order fire effects relies on these advances.

Conclusions

Differences in flammability among species and their potential applications to understanding fire ecology are promising research directions with potential management applications. Observed differences have been attributed to measured variation in physical and chemical traits, fuel structure, and arrangement. Flammability research has suffered from a lack of synthetic analyses of mechanistic drivers and interactions among species. These shortcomings are magnified when studies fail to link results to field-scale outcomes. In spite of these shortcomings, major advances have been made and likely breakthroughs related to the emerging trait-based research fields loom. Challenges will be scaling lab-based research up to field-level fire behavior and impacts. Litter flammability discoveries hold great promise to help clarify patterns in vegetation dynamics and explain plant life history trait evolution. There is much to learn.

Acknowledgments We appreciate discussions with R. Fonda, K. Hiers, E. Banwell, J. Fill, and H. Kuljian—each have added to our understanding of this topic. Funding was provided by our respective institutions and by the US Department of Agriculture and US Department of Interior Joint Fire Science Program (Project 13-1-04-49).

Compliance with Ethics Guidelines

Conflict of Interest The authors state that there are no conflicts of interests to declare

Human and Animal Rights and Informed Consent This article contains no studies with human or animal subjects.

References

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major importance

1. Rothermel RC. A mathematical model for predicting fire spread in wildland fuels. Research Paper INT-115. USDA Forest Service Intermountain Forest & Range Experiment Station, Ogden, UT, USA; 1972. 40 p.
2. Weir JR, Lamb RF. Seasonal variation in flammability characteristics of *Quercus marilandica* and *Quercus stellata* leaf litter burned in the laboratory. Fire Ecol. 2014;9:80–8.
3. Gill AM, Zylstra P. Flammability of Australian forests. Aust For. 2005;68:87–93.
4. Kane JM, Varner JM, Hiers JK. The burning characteristics of southeastern oaks: discriminating fire facilitators from fire impeders. For Ecol Manag. 2008;256:2039–45.
5.•• Mola JM, Varner JM, Jules ES, Spector T. Altered community flammability in Florida's Apalachicola ravines and implications for the persistence of the endangered conifer *Torreya taxifolia*. PLoS ONE. 2014;9:e103933. **This paper is an example of applied flammability research, using flammability to inform land management. This research meshes fuel moisture loss characteristics with burning characteristics to arrive at overall flammability.**
6. Keane RE. Wildland fuel fundamentals and applications. New York: Springer; 2015.
7. Anderson HE. Forest fuel ignitability. Fire Technol. 1970;6:312–9.
8. Martin RE, Gorden DA, Gutierrez ME, Lee DS, Molina DM, Schroeder RA, Sapsis DA, Stephens SL, Chambers M. Assessing the flammability of domestic and wildland vegetation. In: Proceedings of the 12th Conference on Fire and Forest Meteorology; Society of American Foresters Publication 94-02. Bethesda, MD, USA; 1993. p. 130–7.
9. Gill AM, Moore PHR. Ignitability of leaves of Australian plants. Canberra: CSIRO Division of Plant Industry; 1996.
10. White RH, Zipperer WC. Testing and classification of individual plants for fire behavior: plant selection for the wildland-urban interface. Int J Wildland Fire. 2010;19:213–27.
11.• Pausas JG, Moreira B. Flammability as a biological concept. New Phytol. 2012;194:610–3. **This is an important review of the topic in response to a critical response of lab-based flammability research.**
12. Fonda RW. Burning characteristics of needles from eight pine species. For Sci. 2001;47:390–6.

13. Ormeño E, Céspedes B, Sánchez IA, Velasco-García A, Moreno JM, Fernandez C, et al. The relationship between terpenes and flammability of leaf litter. For Ecol Manag. 2009;257:471–82.
14. Mutch RW. Wildland fires and ecosystems—a hypothesis. Ecology. 1970;66:1658–68.
15. Bond WJ, Midgely JJ. Kill thy neighbour: an individualistic argument for the evolution of flammability. Oikos. 1995;73:79–85.
16. Schwilk DW. Flammability is a niche constructed trait: canopy architecture affects fire intensity. Am Nat. 2003;162:725–33.
17. Snyder JR. The role of fire: much ado about nothing? Oikos. 1984;43:404–5.
18. Bradshaw SD, Dixon KW, Hopper SD, Lambers H, Turner SR. Little evidence for fire-adapted plant traits in Mediterranean climate regions. Trends Plant Sci. 2011;16:69–76.
19. Broido A. Flammable—whatever that means. Chem Technol. 1973;3(1):14–7.
20. Fernandes PM, Cruz MG. Plant flammability experiments offer limited insight into vegetation-fire dynamics interactions. New Phytol. 2012;194:606–9.
21. Hiers JK, O'Brien JJ, Mitchell RJ, Grego JM, Loudermilk EL. The wildland fuel cell concept: an approach to characterizing fine-scale variation in fuels and fire in frequently burned longleaf pine forests. Int J Wildland Fire. 2009;18:315–25.
22. Loudermilk EL, O'Brien JJ, Mitchell RJ, Cropper WP, Hiers JK, Grunwald S, et al. Linking complex forest fuel structure and fire behavior at fine scales. Int J Wildland Fire. 2012;21:882–93.
23. Montgomery KR, Cheo PC. Effect of leaf thickness on ignitibility. For Sci. 1971;17:475–8.
24. Susott R, DeGroot WF, Shafizadeh F. Heat content of natural fuels. J. Fire Flammabl. 1975;6:311–25.
25. Broido A, Nelson MA. Ash content: its effect on combustion of corn plants. Science. 1964;46:652–3.
26. Philpot CW. Influence of mineral content on the pyrolysis of plant material. For Sci. 1970;16:461–71.
27. Gill AM, Trollope WSW, McArthur DA. Role of moisture in the flammability of natural fuels in the laboratory. Aust For Res. 1978;8:199–208.
28. Ganteaume A, Lampin-Maillet C, Guijarro M, Hernando C, Jappiot M, Fonturbel T, et al. Spot fires: fuel bed flammability and capability of firebrands to ignite fuel beds. Int J Wildland Fire. 2009;18: 951–69.
29. Kreye JK, Varner JM, Knapp EE. Laboratory fire behaviour in mechanically masticated fuelbeds. Int J Wildland Fire. 2011;20: 308–17.
30.•• de Magalhães RMQ, Schwilk DW. Leaf traits and litter flammability: evidence for non-additive mixture effects in a temperate forest. J Ecol. 2012;100:1153–63. **This study illustrates the effects of mixed-species litters and their resulting non-additive (synergistic) results.**
31. Santana VM, Marrs RH. Flammability properties of British heathland and moorland vegetation: models for predicting fire ignition. J Environ Manag. 2014;139:88–96.
32. Fonda RW, Bellanger LA, Burley LL. Burning characteristics of western conifer needles. Northwest Sci. 1998;72:1–9.
33. Kremens RL, Smith AMS, Dickinson MB. Fire metrology: current and future directions in physics-based methods. Fire Ecol. 2010;6(1):13–35.
34. Schwilk DW, Caprio AC. Scaling from leaf traits to fire behaviour: community composition predicts fire severity in a temperate forest. J Ecol. 2011;99:970–80.
35.•• Engber EA, Varner JM. Patterns of flammability of the California oaks: the role of leaf traits. Can J For Res. 2012;42:1965–75. **This paper evaluates a diversity of leaf and fuelbed physical traits and their effects on oak litter flammability.**
36. Scarff FR, Westoby M. Leaf litter flammability in some semi-arid Australian woodlands. Funct Ecol. 2006;20:745–52.
37. Plucinski MP, Anderson WR. Laboratory determination of factors influencing successful point ignition in the litter layer of shrubland vegetation. Int J Wildland Fire. 2008;17:628–37.
38. Clarke PJ, Prior LD, French BJ, Vincent B, Knox KJE, Bowman DMJS. Using a rainforest-flame forest mosaic to test the hypothesis that leaf and litter fuel flammability is under natural selection. Oecologia. 2014;176:1123–33.
39. Murray BR, Hardstaff LK, Phillips ML. Differences in leaf flammability, leaf traits and flammability-trait relationships between native and exotic plant species of dry sclerophyll forest. PLoS ONE. 2013;8:e79205.
40. Dimitrakopoulos AP, Panov PI. Pyric properties of some dominant Mediterranean vegetation species. Int J Wildland Fire. 2001;10:23–7.
41. Curt T, Schaffhauser A, Borgniet L, Dumas C, Estève R, Ganteaume A, et al. Litter flammability in oak woodlands and shrublands of southeastern France. For Ecol Manag. 2011;261: 2214–22.
42. Ganteaume A, Marielle J, Corinne LM, Thomas C, Laurent B. Effects of vegetation type and fire regime on flammability of undisturbed litter in southeastern France. For Ecol Manag. 2011;261: 2223–31.
43. Ganteaume A, Jappiot M, Lampin C. Assessing the flammability of surface fuels beneath ornamental vegetation in wildland-urban interfaces in Provence (south-eastern France). Int J Wildland Fire. 2013;22:333–42.
44. Thissell A. The role of leaf traits in determining flammability in southern Amazon forests. Pennsylvania State University: University Park. Thesis. 2014.
45. Behm AL, Duryea ML, Long AJ, Zipperer WC. Flammability of native understory species in pine flatwood and hardwood hammock ecosystems and implications for the wildland-urban interface. Int J Wildland Fire. 2004;13:355–65.
46.• Kreye JK, Varner JM, Hiers JK, Mola J. Toward a mechanism for eastern North American forest mesophication: differential litter drying across 17 species. Ecol Appl. 2013;23:1976–86. **This paper illustrates that co-occurring species' litters dry at varying rates that approximate their flammability.**
47. Blackmarr WH. Moisture content influences ignitability of slash pine litter. Research Note SE-173. Asheville, NC: USDA Forest Service Southeastern Forest & Range Experiment Station; 1972. 7 p.
48. Kattge J, Diaz S, 134 co-authors. TRY—a global database of plant traits. Global Chang Biol. 2011;17:2905–35.
49. Beckage B, Platt WJ, Louis JG. Vegetation, fire, and feedbacks: a disturbance-mediated model of savannas. Am Nat. 2009;174:805–18.
50. Gagnon PR, Passmore HA, Platt WJ, Myers JA, Paine CET, Harms KE. Does pyrogenicity protect burning plants? Ecology. 2010;91: 3481–6.
51. Pickett BM, Isackson C, Wunder R, Fletcher TH, Butler BW, Weise DR. Experimental measurements during combustion of moist individual foliage samples. Int J Wildland Fire. 2010;19:153–62.
52.• Santoni PA, Bartoli P, Simeoni A, Torero JL. Bulk and particle properties of pine needle fuel beds—influence on combustion. Int J Wildland Fire. 2014;23:1076–86. **This study quantifies the role of fuelbed permeability on combustion of pine litter.**
53.• Ganteaume A, Jappiot M, Curt T, Lampin C, Borgniet L. Flammability of litter sampled according to two different methods: comparison of results in laboratory experiments. Int J Wildland Fire. 2014;23:1061–75. **This paper finds that flammability differs in intact fuelbeds vs. reconstructed litter in lab burning experiments.**
54. Fonda RW, Varner JM. Burning characteristics of cones from eight pine species. Northwest Sci. 2004;78:322–33.

55. Kreye JK, Kobziar LN, Zipperer WC. Effects of fuel load and moisture content on fire behavior and heating in masticated litter-dominated fuels. Int J Wildland Fire. 2013;22:440–5.
56. Dupuy J. Slope and fuel load effects on fire behavior: laboratory experiments in pine needles fuel beds. Int J Wildland Fire. 1995;5: 153–64.
57. Liu N, Wu J, Chen H, Xie X, Zhang L, Yao B, et al. Effect of slope on spread of a linear flame front over a pine needle fuel bed: experiments and modelling. Int J Wildland Fire. 2014;23:1087–96.
58.• van Altena C, van Logtestijn RSP, Cornwell WK, Cornelissen JHC. Species composition and fire: non-additive mixture effects on ground fuel flammability. Front Plant Sci. 2012;3:art 63. **This study illustrates the effects of mixed-species litters and their resulting non-additive (synergistic) results.**
59. Rundel PW. Structural and chemical components of flammability. In Fire regimes and ecosystem properties, Proceedings of the Conference. Mooney HA, Bonnicksen TM, Christensen NL, Lotan JE, Reiners WA, Technical coordinators. General Technical Report WO-26. USDA Forest Service, Washington, DC, USA; 1981. p. 193–207.
60. Wenk ES, Wang GG, Walker JL. Within-stand variation in understorey vegetation affects fire behavior in longleaf pine xeric sandhills. Int J Wildland Fire. 2011;20:866–75.