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Research Article

Initial Investigation of Seasonal Flammability of three Invasive East Texas Forest Understory Fuels using Thermogravimetric Analysis

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ABSTRACT

East Texas forest understory fuels have become increasingly infested with invasive species which have contributed to greater hazardous fuel loads when combined with decades of fire exclusion and passive management. This study focused on estimating seasonal changes in flammability parameters of invasive yaupon (*Ilex vomitoria*), Chinese privet (*Ligustrum sinense*), and Chinese tallow (*Triadica sebifera*) using thermogravimetric analysis. Foliage and stem samples were collected in the dormant (February) and growing (August) seasons. Differential thermogravimetric (DTG) and proximate analyses were used to estimate species specific flammability parameters related to relative spontaneous ignition temperature (RSIT), gas-phase maximum mass loss rate (GP-MMLR), and combustion duration (GP-CD). Seasonality played a significant role among species RSIT ($p<0.0001$) and GP-CD ($p<0.03$). Proximate analysis VM% was relatively consistent with flammability indices, while the combination of VM% and ash% helped explain some inconsistencies. Yaupon exhibited the greatest foliage ignitability (>RSIT) and combustibility (>GP-MMLR) followed by Chinese privet and tallow. Consequently, yaupon poses a significant year round wildfire and fire management risk. Chinese privets' greater dormant season ignitability may improve prescribed fire control efforts in mid-winter, but may also pose a significant wildfire risk during drought and windy conditions. Chinese tallow stems' greater growing season flammability may enhance integrated control measures using prescribed fire in late summer and early fall. In summary, these data further local knowledge related to seasonal and relative plant flammability and may be useful as additional inputs into custom fuel models, as well as assigning flammability hazard ratings for ornamental vegetation within the wildland-urban interface.

Keywords: GIS forest fire; Wildfire; Flammability; Yaupon; Chinese privet; Chinese tallow

INTRODUCTION

Wildfires are becoming a frequent worldwide problem exacerbated by climate change and decades of increased fuel loading in fire-prone ecosystems [1]. Improved knowledge of the mechanisms governing wildfire initiation and propagation are key components in wildfire planning and management. Wildfire suppression and fire management strategies are often based on fire behavior predictions produced by a host of predictive models. Along with weather and topographic relief information, fire models rely on fuel model data to run mathematical fire spread models. Common fuel model data include metrics related to fuel load and moisture, as well as plant physical characteristics and spatial arrangement. In terms of fuel chemistry, most fuel models use one standardized heat content input (3828 KJ/Kg) [2] which is a measure of complete combustion using oxygen bomb calorimetry [3]. Further limitations exist with heat content metrics due to the rare occurrence of complete combustion in wildland fuels. Based on the limited use of fuel chemistry metrics in fire modeling, improved knowledge of wildland fuel flammability could facilitate improved fire behavior predictions. Thermogravimetric studies have long been used to estimate wildland fuel flammability by using species specific thermal degradation characteristics that serve as data for hazard rankings of common plant species in fire-prone ecosystems [4-8]. Wildfire spread is primarily a function of flaming combustion involving both pyrolytic and oxidative thermal degradation of volatile compounds, hemicellulose, cellulose, and lignin [9]. Recent studies have used both pyrolytic and oxidative thermogravimetric analytic methodologies to gain greater perspective into plant flammability parameters [10].

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Thermogravimetric analysis (TGA) evaluates mass loss as function of temperature under both isothermal and non-isothermal conditions using either an inert (noble gas) or oxidative (air) purge gas [8,10]. Plant flammability studies using inert purge gases are designed to evaluate devolatilization characteristics of biomass under pyrolysis conditions to calculate first-order reaction kinetics [11]. Such kinetic parameters are generally based on model-free isoconversional methods due to greater data reliability and the advantage of evaluating activation energy as a function of conversion degree, which elucidates key combustion characteristics related to reaction mechanisms [8,12]. In addition to kinetic data, TGA studies often include standardized proximate analysis methods that yield percent mass of volatiles, fixed carbon, and ash values to provide additional comparative flammability data [13,14]. Differential Thermogravimetric (DTG) techniques have also been developed to estimate wildland fuel flammability in an air atmosphere by using first derivative degradation profiles to infer ignitability, combustibility, and sustainability metrics [7,15]. Collectively, many TGA studies have yielded promising results, but challenges remain in terms of development of standardized testing methodologies and comparison and validation of experimental data.

Plant flammability testing is further complicated by seasonal changes in plant phenology, physiology, heterogeneous physiographic distributions, and anatomical differences in plant tissue chemistry [16-19]. Plant flammability is primarily driven by moisture content and plant morphology; however, the presence and concentration of volatile compounds play an integral role in estimating flammability [18-21]. Volatile compounds such as terpenes, fats, oils, and waxes contain secondary chemicals or extractives that have high heats of combustion and low heat capacity and molecular weights that increase fuel flammability [20,21]. In addition to volatile compounds, hemicellulose and cellulose are the primary compounds driving flammability and constitute roughly 15-25% and 41-53% of plant mass, respectively [6,13]. Previous research has identified seasonal and spatial variations in plant volatile concentrations in ash juniper (*J. ashei*) in central Texas [22] and gallberry (*I. glabra*) in the southeastern coastal plain of the U.S. [23]. Generally, it is widely accepted that plant flammability is associated with seasonal fuel moisture trends [18], but seasonal variations in plant flammability with respect to variations in volatile compounds, hemicellulose, cellulose, and lignin warrant further research.

East Texas forest understories have become increasingly infested with invasive shrub and tree species, resulting in substantial increases in surface fuel loading [24-26]. Yaupon (*I. vomitoria*) is an aggressive native shrub capable of forming dense, monotypic thickets and is known to contain volatile oils similar to gallberry that exhibit high heat content [27-30]. Chinese privet (*L. sinense*) is a shade tolerant exotic invasive shrub that exhibits rapid regeneration and growth in East Texas forest understories, resulting in significant surface fuel loading [26,31]. Chinese tallow (*T. sebifera*) is an aggressive exotic invasive tree that has expanded in East Texas bottomland hardwood forests due to its prolific seed production and ability to adapt to a wide range of site conditions [32-34]. All three invasive species contribute to increasing biomass of understory fuels available to burn while maintaining horizontal and vertical fuel continuity, which creates a greater potential for increased fire intensity especially during periods of drought [26,35].

The objectives of this study were to improve local knowledge related to seasonal and relative plant flammability using oxidative DTG and proximate analysis data. Two TGA techniques using an air atmosphere were applied to three common invasive East Texas forest understory species to better understand their flammability parameters to provide greater perspective into potential fire hazards and fire management options associated with these locally abundant understory fuels.

RESEARCH METHODOLOGY

Species selection and sampling

Understory species selection was based on local invasive plant abundance relative to greater fuel loading in pine and hardwood forest ecosystems in East Texas. Yaupon was the primary species studied in xeric, upland pine-dominated sites, whereas, Chinese privet and tallow were sampled on more mesic, mixed hardwood-pine sites.

Samples were collected at the Pineywoods Native Plant Center located on the Stephen F. Austin State University campus, Alazan Wildlife Management Area managed by Texas Park and Wildlife Department near Alazan, Texas, and the U.S. Forest Service-Southern Research Station Experimental Forest located on the Angelina National Forest. Study sites were visited during the growing (August) and dormant (February) seasons to account for any seasonal physiological differences in flammability. Foliage and stem samples were collected from five separate specimens of each target species ranging from 0-2 m in height. Specimen height ranges were chosen based on greater susceptibility to prescribed fire [36]. Small diameter ($\leq$ 0.635 cm) stem samples of Chinese tallow were collected during both dormant and growing seasons to account for "leaf off" during the dormant season, and to maintain consistency with potential seasonal variances relative to chemical composition of wood.

Green, undried foliage samples were treated with liquid nitrogen to increase the rigidity of leaf tissue to facilitate grinding. Wood samples were ground in a Thomas Model 4 Wiley mill utilizing a 2 mm, sieve to maintain consistent sample texture. Ground foliage and wood samples were dried at 70°C in an air-convection dryer prior to testing [8].

Thermogravimetric procedure

Standard TGA techniques were performed on a Perkin Elmer Simultaneous Thermal Analyzer 6000 calibrated to manufacturer specifications [37]. Proximate analysis and flammability testing were based on five individual plant samples. Proximate analysis data was estimated using a standard TGA procedure to obtain values for volatile matter (VM%), fixed carbon (FC%), and ash percent (ash%) [38]. Flammability data was estimated using TGA in an oxidative atmosphere by using air as a purge gas at 20 mL min^{-1} with a 10°C min^{-1} linear heating rate ranging from 35-650°C. Subsequent data was further analyzed using Pyris 13.2 software to produce differential thermogravimetric (DTG) degradation profiles that were used to estimate flammability parameters based on DTG peak correlation with gas- and solid-phase combustion [7]. First derivative DTG signatures represent mass loss as a function of temperature and time, and were evaluated for relative spontaneous ignition temperature (RSIT) (Figure 1) and gas-phase maximum

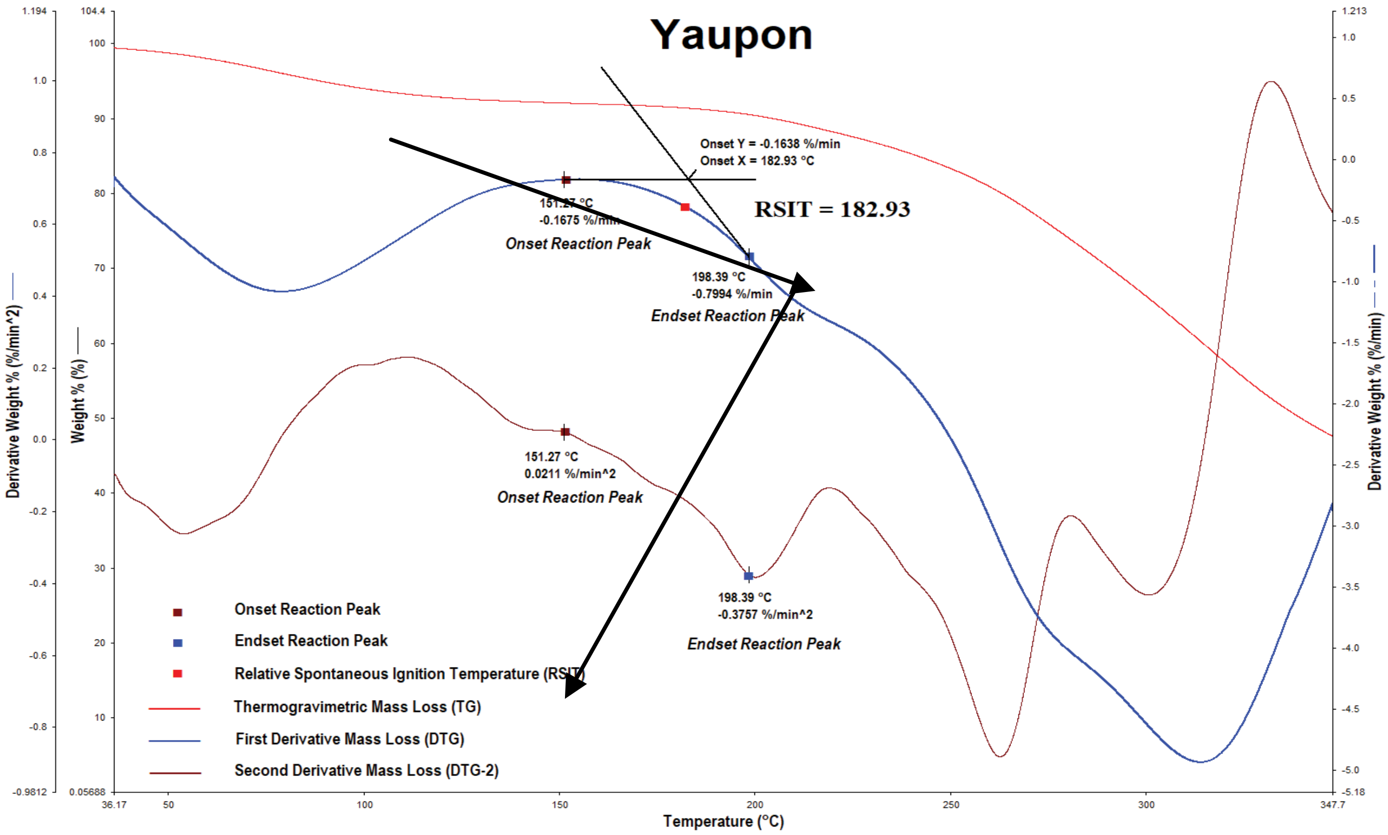

Figure 1: Pyris 13.2 software was used to estimate relative spontaneous ignition temperature (RSIT) for dormant season yaupon using reaction peak tangential lines from first and second derivative thermogravimetric mass loss curves (DTG).

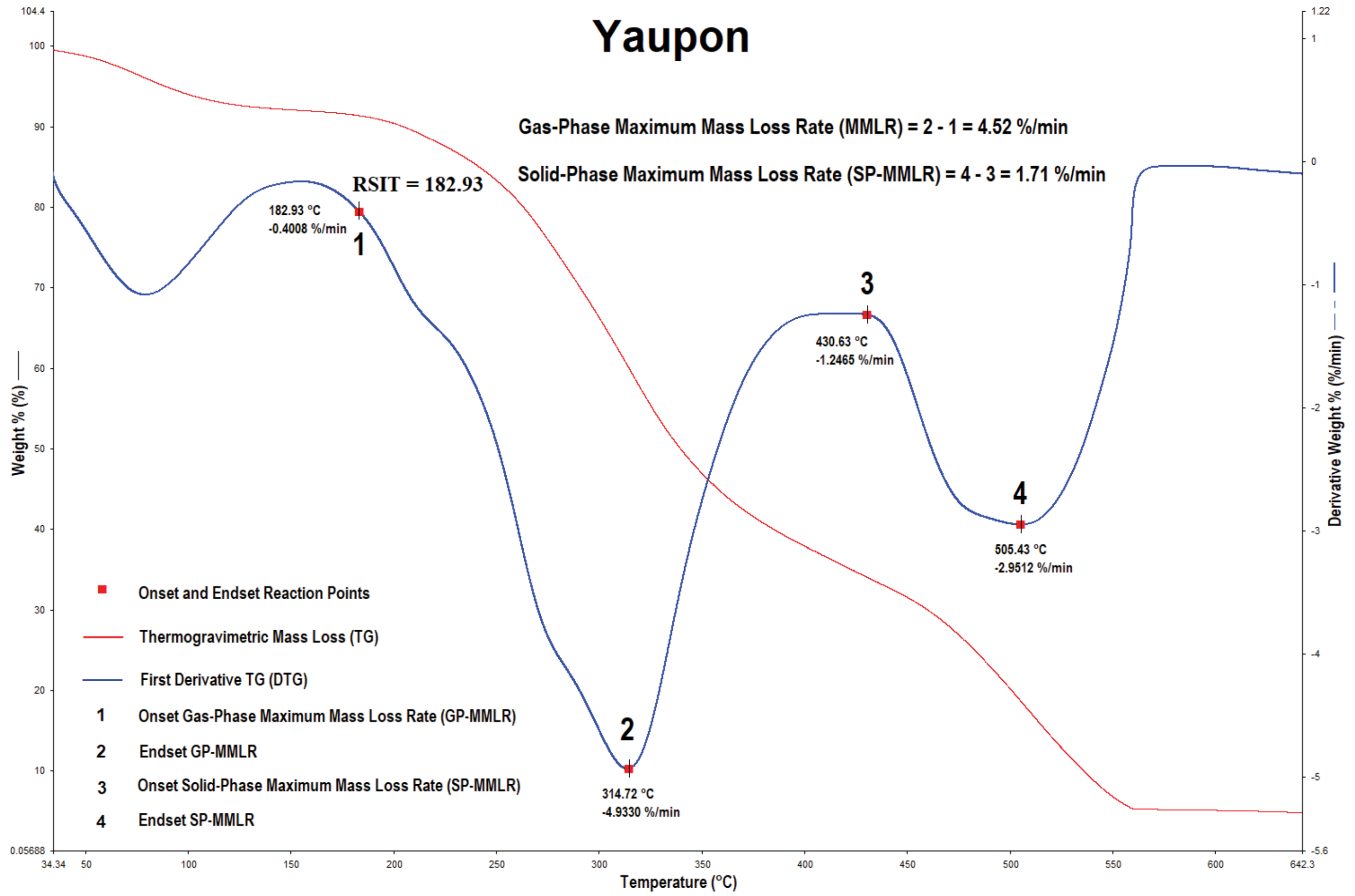

Figure 2: Gas- and solid-phase maximum mass loss rates (GP-MMLR, SP-MMLR) were estimated using the first derivative thermogravimetric mass loss (DTG) curves onset and endset maxima from the two primary DTG peaks.

mass loss rate (GP-MMLR) and combustion duration (GP-CD) by measuring peak onset, maxima, and endset values [7] (Figure 2). The addition of a second derivative peak was also used to elucidate the first onset and endset reaction peak occurring on the first derivative DTG peak representing gas-phase combustion, which greatly improved the accuracy of intersecting tangential lines used to estimate RSIT values (Figure 1). Based on the relative importance of flaming combustion in terms of wildfire propagation [8,9], this study focused on gas-phase combustion rates and durations as relative measures of flammability.

Resulting RSIT, GP-MMLR, and GP-CD data were analyzed using a one- and two-way ANOVA ($p<0.05$) to determine if any significant differences exist between species and season. Yaupon and Chinese privet are evergreen shrubs; therefore, foliage samples were tested using a two-way ANOVA with species and season serving as independent variables. A one-way ANOVA was conducted on Chinese tallow stem with season serving as the independent variable due to leaf off conditions in the dormant season. Descriptive statistics were also used for comparative analysis between flammability and proximate analysis data.

RESULTS

Similar to previous TGA studies [6,7], two distinct DTG peaks representing gas- and solid-phase combustion were observed with all species. Previous studies associated greater RSIT's with lower flash points and piloted ignition temperatures and are therefore representative of more ignitable fuels [39]. According to this assumption, yaupon exhibited the greatest mean RSIT in both growing and dormant seasons (Table 1), classifying it as the most ignitable foliage, followed by Chinese privet and tallow foliage. Yaupon and Chinese privet also exhibited significant differences ($p<0.0001$) with respect to species and season. Seasonal RSIT's for Chinese tallow stem were significantly different ($p<0.0001$) and comparable to seasonal ignitability's of yaupon foliage. Chinese tallow foliage and stem exhibited a considerable difference in mean RSIT, with a 50.86°C differential, thus indicating very low foliage ignitability as compared to highly ignitable stem. All species mean foliage and stem RSIT's trended significantly higher in the growing season with the exception of Chinese privet's greater mean dormant season RSIT. Mean VM% was consistently higher in species with greater ignitability, whereas mean ash% was generally lower in species with greater RSIT (Tables 1 and 2). In summation, yaupon is significantly more ignitable than Chinese privet, which is consistent with past studies suggesting understory species flammability is greater in pine ecosystems as opposed to hardwood ecosystems [40].

Combustibility measures the rapidity in which a material burns and is correlated with greater GP-MMLR's and lower GP-CD's [7,39]. Mean GP-MMLR data for all foliage samples ranged from 2.67-4.51% min^{-1} during both seasons, with yaupon exhibiting the greatest GP-MMLR followed by Chinese privet and tallow (Table 1). In terms of evergreen shrub combustibility, yaupon exhibited a significantly greater mean GP-MMLR ($p<0.0001$) compared to Chinese privet. Chinese tallow stem was the most combustible species with mean GP-MMLR's ranging from 9.96-11.45% min^{-1} in the dormant and growing seasons (Table 1). Mean VM% was consistently higher in species with commensurate increases in GP-MMLR, while mean ash% was generally lower in species with greater GP-MMLR (Tables 1 and 2). Similar to previous findings, species foliage combustibility rankings were consistent with ignitability rankings, with yaupon exhibiting the greatest overall flammability. As expected, all species exhibited greater combustibility in the growing season with the exception of yaupon that had a 0.16% min^{-1} increase in dormant season GP-MMLR.

Measures of sustainability are related to the how long a fuel supports flaming combustion and is correlated with GP-CD. Sustainability is also synonymous with fire front residence time, which can impact fire intensity and spread depending on duration of flaming combustion and varying degrees of heat intensity dictated by species combustibility characteristics [15]. Most TGA studies measure sustainability as a function of time beginning at the onset of spontaneous ignition and concluding at the terminus of the corresponding DTG peak [7,39]. Our results yielded a mean GP-CD of 10.88-15.84 min for all species (Table 1), with Chinese tallow foliage exhibiting the greatest GP-CD followed by Chinese privet and yaupon. Mean GP-CD's for yaupon and Chinese privet were significantly different ($p<0.0001$) with respect to species ($p<0.0001$) and season ($p<0.03$). Similarly, mean seasonal Chinese tallow stem GP-CD's were also significantly different ($p<0.0001$). All species mean GP-CD's and GP-MMLR's were inversely related and in agreement with previous studies combustibility metrics [7,39]. Among GP-CD results, lower values were associated with greater GP-MMLR's, and were generally associated with growing season conditions with the exception of Chinese privet's slight increase

Table 1: Mean growing and dormant season flammability results for Yaupon, Chinese Privet, and Chinese tallow stems.

Flammability	[1]RSIT (°C)	[2]GP-MMLR (%/min)	[3]GP-CD (min)
Season/Species			
Growing			
Yaupon	205.39 (2.95)[4]	4.35 (0.12)	10.88 (0.54)
Chinese privet	166.60 (3.07)	3.32 (0.13)	13.67 (0.38)
Chinese tallow foliage	154.16 (1.78)	2.67 (0.09)	15.84 (0.19)
Chinese tallow stem	205.02 (1.64)	11.45 (1.59)	11.37 (0.18)
Dormant			
Yaupon	183.62 (0.85)	4.51 (0.19)	12.65 (0.29)
Chinese Privet	176.54 (1.19)	3.25 (0.46)	13.05 (0.83)
Chinese Tallow - Stem	181.76 (2.37)	9.96 (1.72)	13.97 (0.50)

[1]Relative spontaneous ignition temperature (RSIT); [2]Gas-phase maximum mass loss rate (GP-MMLR); [3]Combustion duration (GP-CD); [4]Standard deviations in parenthesis.

Table 2: Mean growing and dormant season proximate analysis results for Yaupon, Chinese Privet, and Chinese tallow.

Composition	[1]VM (%)	[2]FC (%)	[3]Ash (%)
Season/Species			
Growing			
Yaupon	79.91 (1.29)[4]	16.01 (0.74)	4.08 (1.79)
Chinese privet	76.29 (2.33)	18.63 (1.35)	5.07 (1.21)
Chinese tallow foliage	74.83 (1.68)	20.41 (1.37)	4.77 (0.64)
Chinese tallow stem	85.57 (1.78)	13.25 (1.17)	1.18 (0.65)
Dormant			
Yaupon	79.55 (1.07)	16.51 (1.37)	3.93 (0.78)
Chinese privet	79.14 (1.73)	15.59 (2.22)	5.27 (0.60)
Chinese tallow stem	83.56 (2.07)	14.47 (1.79)	1.97 (0.34)

[1]Volatile matter (VM%); [2]Fixed carbon (FC%); [3]Ash (ash%) percent; [4]Standard deviations is parenthesis

in dormant season GP-CD. Another noteworthy result was the combination of yaupon's higher dormant season MMLR and GP-CD, which indicates both high combustibility and sustainability.

DISCUSSION

Seasonality had the greatest effect on ignitability for all species. As expected from previous studies [28,29], yaupon was the most ignitable species during both seasons and poses the greatest ignition risk. In contrast, mean dormant season yaupon and Chinese privet RSIT and VM% were fairly comparable, which suggests dormant season prescribed fires targeting Chinese privet may be more effective given adequate fine fuel loading and desirable live fuel moistures. Chinese tallows' low foliage ignitability compared to its high stem wood ignitability may potentially hinder prescribed burn efforts in exiting stands due to the inability to carry fire. Conversely, Chinese tallow that has been masticated or cut and cured in place may be more susceptible to prescribed fire resulting in greater potential top-kill of stump sprouts and improved seed bank control. Proximate analysis results indicating greater VM% were in agreement with RSIT ignitability indices, but ash% indices were somewhat inconsistent as a determinant of ignitability and are consistent with previous studies [30-38].

Foliage combustibility indices were not significantly affected by season; however, Chinese tallow stem was considerably more combustible in the growing season with the overall greatest GP-MMLR. Consequently, the combined effects of Chinese tallows growing season stem combustibility and ignitability would likely improve prescribed fire effects as previously mentioned. Yaupons seasonal combustibility metrics were considerably higher as compared to Chinese privet and tallow foliage, which presents a significant wildfire risk in both seasons. With the exception of Chinese privet, all species exhibited a trend of increasing GP-MMLR based on the inverse relationship of VM% and ash%. Thus, the combination of increasing VM% with subsequent decreases in ash% may serve as an additional metric for confirming combustibility metrics.

Sustainability metrics for all species were significantly affected by season ($p<0.03$). Similar to previous studies, short duration GP-CD's correlated well with greater GP-MMLR's [39,40], thus validating combustibility estimates. Interestingly, yaupon exhibited greater dormant season GP-CD and GP-MMLR, which may potentially amplify dormant season fire intensity based on longer periods of high intensity heat release from flaming combustion. In addition to increased fire intensity, detached foliage may burn for extended time periods in convective columns posing a greater risk for spot fires. Consequently, yaupons' combined high flammability metrics pose a significant hazard to both wildfire and prescribed fire operations. Similar to yaupon, Chinese tallow stem also exhibits combined high flammability metrics which may become hazardous in dense stands under severe drought conditions.

CONCLUSION

Flammability parameters were estimated for three East Texas invasive forest understory species using standard TGA and proximate analysis methodologies. Results were consistent with previous TGA studies and provide new baseline flammability data for locally problematic species. Species flammability metrics can be used for future comparative analysis, as well as an initial quantitative flammability assessment that can serve as hazard classifications for fire resistant plant listings and potential inputs for future fuel models with high densities of invasive species. Yaupon was confirmed as a highly flammable species that poses a year round risk in the wildland-urban interface and is capable of intensifying fire behavior beyond prescribed fire treatment parameters. Chinese privets' greater dormant season ignitability may improve prescribed fire effectiveness earlier in the year; however, early season drought may present a significant wildfire risk during strong wind events. Chinese tallows' highly flammable growing season stem wood may also improve integrated control measures using prescribed fire. Collectively, these data provide greater knowledge of species flammability based on fuel chemistry, but further research is necessary to validate and compare experimental flammable indices to different testing methodologies and full scale experimentation.

AUTHOR CONTRIBUTIONS

Conceptualizations, MBT, BPO; methodology, MBT, BPO, ASF; formal analysis, MBT ASF; investigation MBT; data curations MBT, BPO; writing-original draft preparation, MBT, BPO; writing-review and editing, MBT, ASF, WCC, BPO, IH; supervision, BPO; project administration and funds acquisition BPO. All authors have read and agreed to the published version of the manuscript.

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