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Research Article

Preliminary Flammability Assessment of Sea Buckthorn from The Netherlands Compared to Known Flammable Shrubs of the Southern and Western US

Michael B. Tiller[1], **Brian P. Oswald**[1]*, **Mathijs Schuijn**[2]

[1]*Stephen F. Austin State University, Arthur Temple College of Forestry and Agriculture, 419 East College Street, Nacogdoches, TX 75962, USA;* [2]*Wolf Fire Safety, The Netherlands*

ABSTRACT

Sea buckthorn (*Hippophae rhamnoides*) is a common coastal species in The Netherlands that potentially burns with extreme energy levels. In this region of Europe that is experiencing increases in wildfire events, the need to gain a greater understanding of energy released when this species burns will improve fire behavior predictions. The objective of this study was to conduct an initial investigation into the foliage flammability of sea buckthorn compared to a common southern United States native shrub known for its flammability, yaupon (*Ilex vomitoria*), and two common dominant shrub species in California chaparral, chamise (*Adenostoma fasciculatum*), and manzanita (*Arctostaphylos* spp.). Flammability parameters were evaluated using thermogravimetric analysis (TGA) and oxygen bomb calorimetry to estimate relative spontaneous ignition temperature (RSIT), gas-phase maximum mass loss rate (GP-MMLR), gas-phase combustion duration (GP-CD), volatile matter%, fixed carbon%, ash%, and net heat content (NHC). Sea buckthorn exhibited similar ignitability (<RSIT) with the other species, as well as similar combustibility (>GP-MMLR) to yaupon. Sea buckthorn and yaupon shared similar NHC values and subsequent fire behavior outputs. Proximate analysis for VM% and FC% were varied, but low ash% values correlated with slightly lower RSIT's for sea buckthorn and chamise. Anecdotal information from a 2019 prescribed burn along the coast of The Netherlands highlighted significant fire behavior, and shows similarities with these species in two North American ecosystems.

Keywords: Forest fire; Wildfire; Flammability; Yaupon; Sea buckthorn; Chaparral

INTRODUCTION

Decades of increasing fuel loads and climate change have contributed to wildfires becoming a worldwide issue [1]. Regions of the world that have not acquired a proactive wildland fire culture as is found in the United States could benefit from greater knowledge of fuel flammability estimates that aid in hazardous fuel classification and fire behavior predictions. Comprehensive hazardous fuel classifications often include four key pyric properties that include ignitability, combustibility, sustainability, and consumability [2,3]. This study focused on ignitability, combustibility, and sustainability as they pertain to gas-phase combustion. Simply defined, ignitability is the minimum temperature required for ignition or time to ignition when exposed to a heat source; combustibility is the rapidity in which biomass burns under flaming combustion; and sustainability is the duration of time biomass supports flaming combustion after a heat source is removed. As such, these mechanisms form the fundamental properties governing wildfire initiation and propagation and can serve as key metrics in developing hazardous fuel classifications, as well as potential inputs into fire models with custom fuel model options. In terms of fuel chemistry, most fuel models use one standardized heat content input (18.61 $MJkg^{-1}$) [4], which is a measure of complete combustion using oxygen bomb calorimetry [5]. Since wildland fuels rarely exhibit complete combustion in an oxygen enriched atmosphere, estimating heat content metrics as a primary source of fuel thermal characteristics may be somewhat misleading due to variability of volatile extracts, hemicellulose, cellulose, and lignin among wildland fuels.

Thermogravimetric studies have been used to estimate wildland fuel flammability by using species-specific thermal degradation characteristics that serve as hazard rankings of common plant species in fire-prone ecosystems [6-10]. Wildfire spread is primarily driven by the pyrolytic and oxidative thermal degradation of volatile compounds, hemicellulose, cellulose, and lignin [10,11], and recent studies into plant flammability parameters have used both pyrolytic and oxidative thermogravimetric analytic (TGA) methodologies. TGA estimates mass loss as a function of temperature under two

Correspondence to: Brian P. Oswald, Stephen F. Austin State University, Arthur Temple College of Forestry and Agriculture, 419 East College Street, Nacogdoches, TX 75962, USA, Tel: +9366457990; E-mail: boswald@sfasu.edu

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conditions (isothermal and non-isothermal), utilizing either an inert (noble gas) or oxidative (air) purge gas [10,12]. Plant flammability studies using the former are designed to evaluate biomass devolatilization under pyrolysis conditions to calculate first-order reaction kinetics or model-free isoconversional methods [11,13,14]. By contrast, differential thermogravimetric (DTG) techniques have been developed to estimate wildland fuel flammability in an air atmosphere to infer ignitability, combustibility, and sustainability metrics [9,15]. Many TGA studies also include standardized proximate analysis methods that yield percent mass of volatiles, fixed carbon, and ash values to provide additional comparative flammability data [16,17].

Natural variation associated with plant flammability can be attributed to differences in species-specific intrinsic properties related to phenology, physiology, anatomical differences, and variability in plant tissue chemistry [18-21]. Plant flammability is further influenced by extrinsic factors related to climate, local weather patterns, seasonal weather trends, and physiographic differences among and within ecosystems [18,19,22]. However, many studies acknowledge the fundamental importance of fuel moisture as a primary driver of plant flammability, while other studies suggest volatile compounds also play an integral role in estimating flammability [20,23,24]. Volatile organic 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 [23,24], whereas hemicellulose and cellulose are the primary drivers of flammability and constitute roughly 15-25% and 41-53% of plant mass, respectively [8,15].

Sea buckthorn (*H. rhamnoides*) is a common coastal species in The Netherlands that potentially burns with extreme energy levels [25,26]. Prior research evaluating its chemical composition focused on its potential health benefits rather than its thermal properties. Sea buckthorn is commonly found in dense thickets along the coast of the Netherlands within areas with heavy recreation activities, placing it as one of the more hazardous plant species along the coast. Yaupon (*I. vomitoria*) is an aggressive native shrub in the southeastern United States capable of forming dense, monotypic thickets and is known to contain volatile extracts that exhibit high heat content [26-30]. As a result, yaupon contributes to increasing flammable biomass of understory fuels while maintaining horizontal and vertical fuel continuity, which creates a greater potential for increased fire intensity, especially during periods of drought [26,31]. Chamise (*A. fasciculatum*) and manzanita (*Arctostaphylos* spp.) are common shrub species within the California chaparral ecotype of western United States. Chamise is a chaparral species that exhibits a high concentration of volatile compounds and readily burns with great intensity [32-34).

The objective of this study was to conduct a preliminary foliar flammability comparison of sea buckthorn to three well-known flammable shrubs species within the US using TGA and oxygen bomb calorimetry. Estimated flammability metrics included relative spontaneous ignition temperature (RSIT), gas-phase maximum mass loss rate (GP-MMLR), gas-phase combustion duration (GP-CD), volatile matter%, fixed carbon%, ash%, and net heat content (NHC). Relative plant flammability was estimated using oxidative DTG and proximate analysis data. Based on anecdotal observations from a recent prescribed burn, the authors hypothesized that if sea buckthorns' flammability metrics correlated well with more commonly studied North American species, preexisting fire behavior knowledge of Northern American species could assist in hazardous fuel classifications and estimating fire behavior in the Netherlands where sea buckthorn dominates.

RESEARCH METHODOLOGY

Foliage samples were collected at the following locations: sea buckthorn, Island of Terschelling in the province of Friesland, Netherlands, June 2018; chamise and manzanita, El Moro Elfin Forest Natural Area, Los Osos, California, August 2018; and Yaupon, Post Oak Savannah Ecoregion, College Station, Texas, August 2017. Due to shipping constraints, sea buckthorn, chamise, and manzanita samples were reduced to individual plant specimens with relatively small foliage sample sizes which constrained the number of tests that could be conducted on each species. However, a more extensive data set was used for yaupon due to ongoing research at Stephen F. Austin State University. Samples were ground and dried at 40°C for 48 hours to avoid loss of volatiles, and passed through standard mesh sieves to obtain 35 mesh fractions.

Oxygen bomb calorimetry (OBC) was performed using a model 1301 Parr calorimeter standardized with benzoic acid according to manufacturer specifications [35]. Heat of combustion corrections were determined by using ignition wire corrections combined with standardized water vapor corrections of 1.26 MJ kg^{1}, which adjusts gross heat content (GHC) to NHC values [17]. Samples shipped from abroad underwent five OBC tests, while yaupon was tested based on a series of five OBC tests for five individual plant specimens totaling 25 tests. Further comparison of mean NHC data was accomplished by estimating fire behavior related to fireline intensity (FI) and flame length (FL) using standard methodologies outlined by [36] in conjunction with standard fuel model data [2]. Fuel model data was correlated with species ecosystem similarities, which corresponded with dry and humid climate high shrub load fuel models. Rate-of-spread was set at high-moderate conditions (0.20 m/s) to simulate potential wildfire conditions. FI and FL were calculated as follows:

Heat per unit area (HPA) (kJ/m^2) = Fuel Load (g/m^2) × NHC (kJ/g)

FI (kW/m) = HPA × Rate-of-spread (m/s)

FL (m) = 0.078 × $FI^{0.46}$

Thermogravimetry was conducted using a Perkin Elmer Simultaneous Thermal Analyzer (STA) 6000 calibrated to manufacturer specifications. Proximate analysis data was estimated using a standard TGA procedure to obtain values for volatile matter (VM%), fixed carbon (FC%), and ash percent (ash%) [37]. Samples collected from abroad underwent two proximate analysis tests, while yaupon underwent five tests due to greater sample availability. Flammability data was estimated 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 [9]. First derivative DTG signatures represent mass loss as a function of temperature and time, and were evaluated for relative spontaneous ignition temperature (RSIT), gas-phase maximum mass loss rate (GP-MMLR), and combustion duration (GP-CD) by measuring peak onset, maxima, and endset values [9]. Samples underwent three oxidative TGA tests, except yaupon which underwent five tests.

RESULTS

Thermogravimetric data from oxidative tests yielded two distinct DTG peaks representing gas- and solid-phase combustion for all species, which is consistent with past TGA studies [8,9]. Measures of ignitability, combustibility, and sustainability are all key metrics of relative flammability associated with gas-phase combustion. Previous TGA studies have identified spontaneous ignition as the onset temperature of the first DTG peak signifying gas-phase combustion [9,12]. Further analysis suggested that greater spontaneous ignition temperatures were associated with lower flash points and piloted ignition temperatures, thus fuels with higher spontaneous ignition temperatures were more ignitable [7]. However, a recent plant flammability study using Simultaneous Thermal Analysis –Infrared Spectroscopy (STA-IR) matched RSIT values to the onset of CO_2 release (IR signature) among plant foliage samples, and found shorter times to ignition were correlated with lower RSIT values; thus suggesting lower RSIT values indicate greater ignitability [38]. Based on [38] and the fact that yaupon and chamise have been reported and anecdotally observed has being highly flammable, it is reasonable to assume low RSIT values are representative of more ignitable foliage [28,32-34]. Sea buckthorns' mean RSIT of 174.44°C is slightly more ignitable than chamise and manzanita with a RSIT of $\sim 175.00^{\circ}C$ (Table 1). Though the data indicates sea buckthorn as the most ignitable species, the range of ignitability among all species is very similar when considering sample variability. Therefore, initial ignitability estimates place sea buckthorn in the same hazard classification of known flammable shrubs in the southern and western US.

Fire spread and intensity are often associated with fuel combustibility, and therefore a key component in overall fuel flammability. Combustibility estimates using TGA data are associated with GP-MMLR's and GP-CD's [7-9,15]. Sea buckthorn and yaupon exhibited similar combustion characteristics in terms of mean GP-MMLR and GP-CD, ranging from 4.05-4.15% min^{-1} and 12.89-13.69 min, respectively (Table 1). In contrast, chamise and manzanita exhibited slightly lower GP-MMLR's ranging from 3.43-3.47% min^{-1}, while chamise maintained a similar mean GP-CD of 13.03 min compared to sea buckthorn and yaupon. Interestingly, manzanita exhibited a significantly higher mean GP-CD of 15.01 min, suggesting greater sustainability as compared to sea buckthorn, yaupon, and chamise. It is also noteworthy to identify similarities among lower GP-CD's of sea buckthorn, yaupon, and chamise, which further suggest greater combustibility based on the rapidity of gas-phase combustion. In terms of VM% and ash%, sea buckthorn and chamise exhibited similar mean VM% and ash% ranging from 1.63-1.98% and 77.04-77.55%, respectively (Table 2). Yaupon and manzanita exhibited similar mean ash% ranging from 3.83-4.22%, while mean VM% ranged from 78.65-80.14%. In sum, sea buckthorn exhibits quite similar flammability characteristics compared to yaupon and chamise.

Foliage heat content is the primary biochemical determinant for predicting plant flammability in many common fire behavior fuel models, and is often a set standard value of 8000 BTU/lb or 18.61 MJkg^{1} for all fuel types [4,5]. Though this standard yields consistency across all fuel types, some disparity may exist between the upper and lower flammable limits of some wildland fuels, as well as differences in fuel bed composition and subsequent variances among species densities. Nevertheless, standardized NHC values have yielded reasonable results across many fire models. Mean NHC values in this study ranged from 17.98-19.27 MJ/kg^{1} (Table 3) and when averaged yielded 18.63 MJ/kg^{1}, which aligns well with the standardized heat content value. Estimated fire behavior outputs for experimental data using fireline intensity (FI) and flame length (FL) yielded variable FI's ranging from 17.98-19.27 kWm^{-1}, while FL's exhibited little variability ranging from 2.67-2.76 m. Interestingly, when mean NHC data was compared

Table 1: Mean flammability results for sea buckthorn, yaupon, manzanita, and chamise. Sea buckthorn was collected in The Netherlands on the Island of Terschelling in June 2018, yaupon was collected in east Texas in February 2017, and manzanita and chamise were collected in Los Osos, California in August 2018.

Flammability	[1]RSIT (C°)	[2]GP-MMLR (%/min)	[3]GP-CD (min)
Species			
Sea buckthorn	174.44 (0.73)[4]	4.15 (0.03)	13.69 (0.33)
Yaupon	176.00 (0.69)	4.05 (0.23)	12.89 (0.24)
Manzanita	175.50 (0.24)	3.47 (0.06)	15.01 (0.09)
Chamise	175.18 (1.19)	3.43 (0.05)	13.03 (0.16)

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

Table 2: Mean proximate analysis results for sea buckthorn, yaupon, manzanita, and chamise. Sea buckthorn was collected in The Netherlands on the Island of Terschelling in June 2018, yaupon was collected in east Texas in February 2017, and manzanita and chamise were collected in Los Osos, California in August 2018.

Composition	[1]VM (%)	[2]FC (%)	[3]Ash (%)
Species			
Sea buckthorn	77.55 (0.10)[4]	20.48 (0.10)	1.98 (0.19)
Yaupon	80.14 (0.68)	16.04 (0.84)	3.83 (0.91)
Manzanita	78.65 (0.18)	17.13 (0.06)	4.22 (0.13)
Chamise	77.04 (0.25)	21.34 (0.25)	1.63 (0.00)

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

with mean GP-MMLR data, an inverse relationship was observed between expected GP-MMLR's and species mean NHC values (Figure 1). For example, sea buckthorn exhibited the lowest mean NHC value, yet it produced the greatest GP-MMLR. This similar trend was observed with all species, which suggests that GP-MMLR maybe a viable metric for improving plant flammability estimates among plant species in conjunction with NHC values.

DISCUSSION

Mean flammability metrics for sea buckthorn, yaupon, and chamise exhibited very similar metrics for RSIT and GP-CD, thus suggesting sea buckthorn can be classified as a hazardous shrub in terms of overall flammability. In addition, sea buckthorn exhibited the lowest mean RSIT combined with the greatest mean GP-MMLR, ranking it the most ignitable and combustible species in this study. Interestingly, sea buckthorn recorded the lowest mean NHC among species, yet produced the greatest experimental flammability characteristics in terms of RSIT and GP-MMLR for all species. Sea buckthorn also exhibited the second highest GP-CD, which suggests high combustibility combined with moderate sustainability that could lead to greater residence times of high heat emissions, as well as spot fire potential related to burning foliage entrained in convective columns. Sea buckthorn also yielded the lowest mean NHC value resulting in the lowest estimated fire behavior values for FI and FL. Although FL estimates remained consistent among species, the greatest difference was observed in sea buckthorns' FI, differing by as much as 129.36 kWm^{-1}, compared to chamise which shares similar flammability characteristics with respect to oxidative TGA metrics. In this case, differences among species FI was negligible, and therefore demonstrates the general applicability of the current standardized NHC value used in common US fire models. The combination of GP-MMLR and GP-CD could be further used as weighted metrics to customize standard NHC values based on varying degrees of shrub densities existing within target fuel beds, potentially yielding improved fire behavior estimates. More importantly, oxidative TGA metrics could be applied to a hazardous fuel classification system aimed at safeguarding life and property in and around populated areas at risk for wildfire.

Proximate analysis results for VM% contributed little to flammability estimates and showed no correlating trends among mean NHC and TGA oxidative flammability metrics. However, species with lower mean ash% exhibited slightly lower mean RSIT's, thus indicating ash% may play a role in estimating subtle differences in RSIT metrics. Combustibility metrics for GP-MMLR trended higher for sea buckthorn and yaupon which correlated with the humid climates theses shrubs occupy. Conversely, chamise and manzanita exhibited lower GP-MMLR's correlating with California's dry Mediterranean climate. Mean NHC values followed an inverse trend as GP-MMLR, with lower values associated with the humid climate shrubs and higher values associated with the dry climate shrubs.

A non-quantified assessment of the fire behavior in sea buckthorn was observed in February 2019 on the island of Terschelling in the Netherlands. The Netherlands was under drought conditions, with

Table 3: Mean oxygen bomb calorimetry results measured as net heat content (NHC) for sea buckthorn, yaupon, manzanita, and chamise. Subsequent NHC values were used to estimate fireline intensity and flame length using equations from Byram (1959) and similar fuel model data from Scott and Burgan (2005) for each species respective ecosystem.

Fuel Characteristics	[1]NHC (MJkg^{-1})	[2]FI (kW/m)	[3]FL (m)
Species			
Sea buckthorn	17.98 (0.24)[4]	2167.72	2.67
Yaupon	18.22 (0.31)	2196.90	2.69
Chamise	19.05 (0.22)	2297.08	2.74
Manzanita	19.27 (0.20)	2323.76	2.76

[1]Net heat content (MJkg^{-1}); [2]Fireline intensity (kW/m); [3]Flame length (m); [4]Standard deviation in parenthesis. Fire behavior outputs were estimated using Scott and Burgan (2005) fuel models FM SH8 for sea buckthorn and yaupon and FM SH5 for chamise and manzanita.

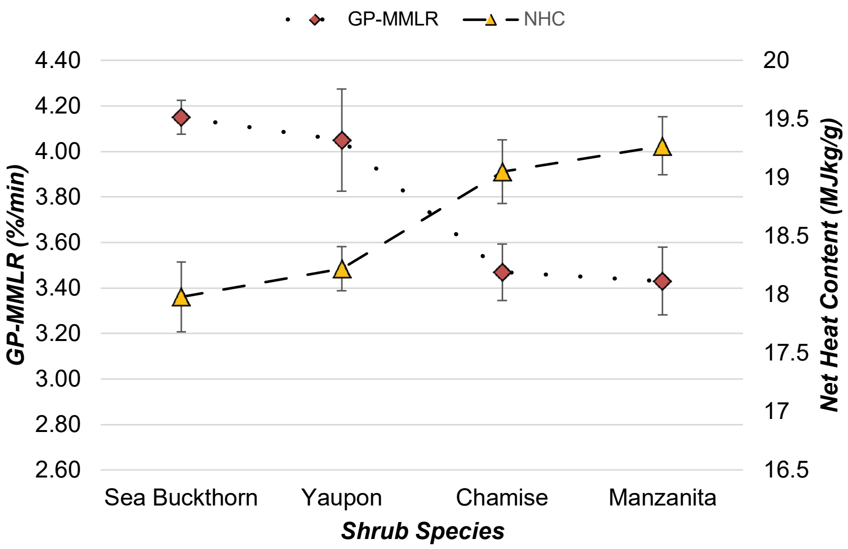

Figure 1: Net heat content (NHC) and gas-phase maximum mass loss rate (GP-MMLR) for sea buckthorn, yaupon, chamise, and manzanita with 95% confidence intervals.

(A) (B)

Figure 2: Prescribed burning in sea buckthorn (A) and yaupon (B).

33% of normal rainfall three months prior to the burn, with the last measurable precipitation of 0.8mm four days prior to burning. For the previous six day fire weather forecast, maximum temperatures and minimum humidity (RH) ranged from 7.3–10.0°C and 53-89%. On the day of the fire, weather during ignition (13:00-17:00) was RH 82-90% and wind SW 1.9-4.5 m/s. The ignition method was a head fire secured by flanking fire and a stripping black fire downwind. Observed fire behavior was similar than those observed in East Texas yaupon (Figure 2).

CONCLUSION

Sea buckthorn exhibited comparable ignitability, combustibility, and sustainability to yaupon and chamise. While VM% was quite variable between species, lower ash% contributed to slight increases in ignitability for sea buckthorn and chamise with slightly lower RSIT's as compared to yaupon and manzanita. Sea buckthorn and yaupon exhibit similar NHC and subsequent FI and FL. Overall, sea buckthorn exhibits comparable flammability to multiple shrubs in both humid and dry climates of the United States, and the estimated FI's of $\sim 2000\, kW/m$ for all species suggests serious control problems under the prescribed rate-of-spread condition. Based on sea buckthorn's flammability estimates, this shrub would be classified as a hazardous species that warrants caution in areas of moderate to high shrub densities in and around human development and recreation areas. Specifically, extreme caution should also be exercised during periods of drought culminating in critical fuel moistures in combination with hot, dry, windy weather which can lead to explosive fire growth upon ignition. Though higher temperatures and drier offshore winds would likely exacerbate fire behavior in the coastal dunes, particular attention should be given to Atlantic low pressure systems that produce strong onshore winds capable of producing wind-driven fires that move inland toward greater human populations and infrastructure.

AUTHOR CONTRIBUTIONS

Conceptualizations, MBT, BPO; methodology, MBT, BPO, MS; formal analysis, MBT, BPO; investigation MBT, MS; data curations MBT, BPO; writing-original draft preparation, MBT, BPO; writing-review and editing, MBT, BPO; 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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