Forest Research
Open Access

Oswald et al., Forest Res 2017, 6:2
DOI: 10.4172/2168-9776.1000208

Research Article Open Access

Biomass Estimations of Invasives Yaupon, Chinese Privet and Chinese Tallow in East Texas Hardwood and Pine Ecosystems

Tiller MB[1], Oswald BP[1]*, Frantzen AS[2], Conway WC[3] and Hung I[1]

[1]*Arthur Temple College of Forestry and Agriculture, Stephen F Austin State University, Nacogdoches, USA*
[2]*Department of Chemistry and Biochemistry, Stephen F Austin State University, Nacogdoches, USA*
[3]*Department of Natural Resources Management, Texas Tech University, Lubbock, USA*

Abstract

Forest understory fuels can have profound effects on fire behavior and crown fire initiation. Accurate fire behavior prediction in understory fuels is an essential component for estimating fire intensity and severity during wildfire and prescribed fire events. This study focused on estimating temporal and seasonal changes in fuel loading parameters associated with the expansion of invasive yaupon (*Ilex vomitoria*), Chinese privet (*Ligustrum sinense*), and Chinese tallow (*Triadica sebifera*) in East Texas pine and hardwood ecosystems. Fuel loading data of invasive species infested sites indicated significant increases in understory biomass when compared to 1988 estimates, suggesting a clear need to revise regional fuel models. Multiple and simple regression biomass prediction equations were developed for all three-invasive species to facilitate fuel load estimates. These improved prediction equations will enhance fire management efforts as well as invasive species mitigation efforts in east Texas.

Keywords: Invasive; Biomass; Texas; Wildfire

Introduction

Forested ecosystems in East Texas have undergone significant temporal and spatial changes in plant community structure and composition, attributed to fire exclusion, altered fire regimes, land use changes, human-induced forest fragmentation, and changing forest management practices [1-5]. In addition, dense woody understory growth is common on timber tracts due to costly understory treatments [3]. Increasing human development in suburban areas from nearby urban centers has added to the Wildland Urban Interface (WUI) in suburban communities, presenting a greater risk for structure loss during wildfires [6,7]. At the same time, the use of prescribed fire for managing woody understory growth has increased throughout East Texas due to more intensive silvicultural practices, endangered species habitat restoration, hazardous fuels reduction, and recent interest in reestablishing longleaf pine (*Pinus palustris*).

Little research has investigated fuel loading in East Texas forest understory strata that have become infested with native and exotic invasive species [8-10]. Changes in current understory plant composition and structure via establishment of native and exotic invasive species presents inherent problems related to fire behavior prediction by potentially increasing understory biomass and ladder fuels [9,11-13], and regional understory fuel strata have not been updated in East Texas fuel models since 1988 [14]. Assessing these fuel models presents many challenges due to dynamic changes in plant community structure and composition, driven by the above changes [1-4,15]. Altered fire regimes have severely impacted these ecosystems, resulting in greater susceptibility for invasive species encroachment and formation of dense, monotypic thickets of understory fuels [3,12,16]. The combined effects of these human-related disturbances can further favor invasive species proliferation and persistence in forest understories.

Contemporary fuel models utilize a variety of properties of wildland fuels (e.g., fuel loads, fuel volatility) to improve accuracy of fire behavior prediction by accounting for differences among all vegetative species [17]. Improved fire behavior prediction and modeling gained from incorporating new and updated comprehensive fuel model parameters can be a critical component in fire management relative to safe, effective prescribed burn planning, wildfire risk assessment, and development of safe, effective wildfire strategies and tactics. Current fuel model data specific to East Texas forests are limited by general fuel parameters [11,18] which do not account for dynamic spatial and temporal changes in fuel composition currently found in the southeastern United States [4] as native and exotic species establishment in regional forest understory fuels have influenced dynamic changes to understory fuel composition and structure.

Three invasive species of primary concern were chosen for this study. Yaupon (*Ilex vomitoria*) is a native invasive shrub that forms dense, monotypic stands in forest understories suppressing native herbaceous, shrub, and tree regeneration, leading to reduced biodiversity and greater fuel loads [4,16,19]. Yaupon has been identified as highly flammable and is not recommended for landscaping [20,21]. Chinese privet (*Lugustrum sinense*) is a nonnative shrub that forms dense, monotypic stands primarily in mesic, bottomland hardwood forests with increasing encroachment into xeric, upland sites; dense stands are associated with decreased biodiversity and poor hardwood and pine regeneration [22-24]. Chinese tallow (*Triadica sebifera*) is an invasive, nonnative tree commonly occurring in mesic, bottomland hardwood sites with some extension into upland sites; when established, Chinese tallow suppresses native species, reduces biodiversity, and alters wildlife habitat [12,25,26]. Chinese tallow and privet are not typically targeted for wildland fuel reduction due to their occurrence on mesic sites; however, they could alter fuel loads and fire behavior in a variety of systems.

***Corresponding author:** Oswald BP, Arthur Temple College of Forestry and Agriculture, Stephen F Austin State University, College Street, Nacogdoches, USA, Tel: 9364682275; E-mail: boswald@sfasu.edu

Received August 24, 2017; **Accepted** September 06, 2017; **Published** September 08, 2017

Citation: Tiller MB, Oswald BP, Frantzen AS, Conway WC, Hung I (2017) Biomass Estimations of Invasives Yaupon, Chinese Privet and Chinese Tallow in East Texas Hardwood and Pine Ecosystems. Forest Res 6: 208. doi: 10.4172/2168-9776.1000208

Objectives

The goal for this research was to obtain qualitative and quantitative descriptions of yaupon, Chinese privet, and Chinese tallow relative to their increased occurrence in regional fuel models and create total aboveground biomass regression models. The specific objectives were to:

a) Quantify species-specific fuel loads in local forest ecosystems that have exhibited increases in focal species abundance and density since the last fuel loading appraisal was conducted in 1988.

b) Using updated fuel loading parameters in BehavePlus, examine differences in fire behavior outputs when compared to standardized fuel models outlined in 1988 for East Texas.

c) Estimate invasive species total aboveground biomass indices occurring in mixed pine-hardwood stands based on height and basal diameter data using multiple and simple regression analyses.

Methods

Site selection and description

Three forest ecosystems, (pine, hardwood, and mixed pine-hardwood), comprised the criterion for research site selection to represent spatial diversity for the focal invasive species. A fourth site served as a control and was a mixed pine-hardwood stand with an understory comprised of native species.

Chinese tallow and privet are typically found on mesic bottomland hardwood and mixed hardwood-pine sites; therefore, site selection was limited to hardwood-dominated ecosystems where both species were abundant. The 835 ha Alazan Wildlife Management Area (WMA) located in Alazan, Texas (Figure 1) had existing thickets of Chinese tallow. The Pineywoods Native Plant Center (PNPC), a 17-ha garden located on the Stephen F. Austin State University (SFASU) campus in Nacogdoches, Texas (Figure 1), consisted of a mixed hardwood-pine ecosystem with significant Chinese privet in the understory.

Two study sites were selected for assessing yaupon fuel loading. The George W. Pirtle Scout Reservation (GWPSR) is located in Panola County, Texas (Figure 1), and the Stephen F. Austin Experimental Forest (SFAEF) in Alazan, Texas (Figure 1) possessed abundant yaupon across pine and mixed pine-hardwood ecosystems. The sites consisted of 25 ha for the GWPSR and 21.6 ha for the SFAEF. The SFAEF exhibits a diverse understory composition of native flora resulting from past experimental management practices and also provided a control site (SFAEF-C) of 22.5 ha free of target invasive species.

Field measurements

Site inventories were performed to estimate mean basal area, tree density, basal area of dominant species, percent canopy cover, aspect, slope, and species composition, utilizing a line-point sampling method with a 10 BAF prism (0.04 ha plot), spherical convex densiometer (percent canopy cover), and a Silva model 515 compass to estimate slope and aspect. Sampling plots were randomly selected within each site, using a random plot generator in ArcMap. The number of plots used was relative to the total area of each site and stand homogeneity. Five plots per site were used for Alazan WMA, PNPC, SFAEF, and SAFEF-C with <22.5 ha areas, whereas 12 plots were sampled on GWPSR due to its greater area (25 ha) and stand heterogeneity.

Fuel loading plots were located based on the presence of target invasive species and stand complexity, and the number of sample points

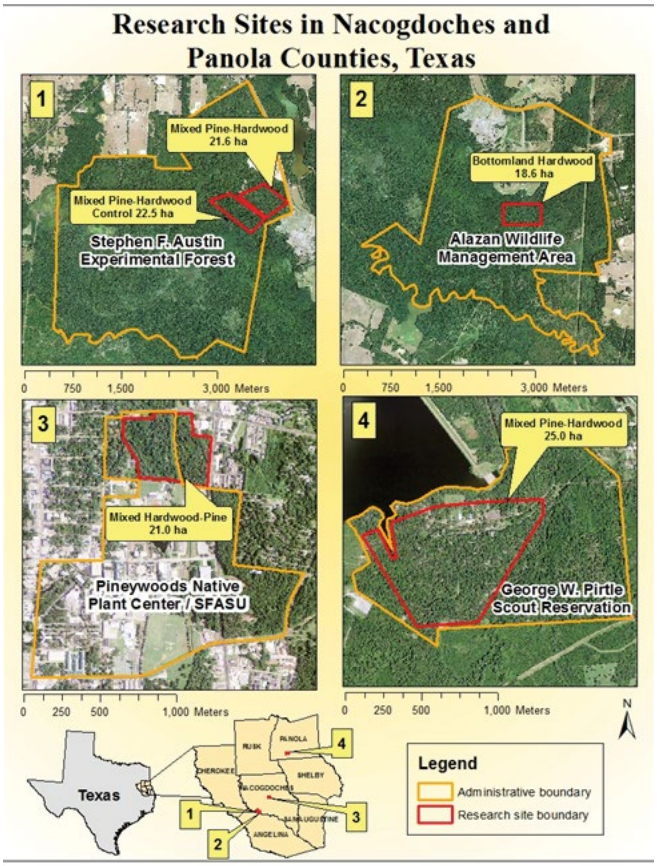

Figure 1: Yaupon, Chinese privet, and Chinese tallow research site locations in East Texas.

were determined with a recommended 15-20 sample points per 20.2 ha compartment with similar fuel distributions [27]. Plot locations were referenced from predetermined transects, and were spaced a minimum of 40 m apart. Each plot consisted of a 15.2 m plot grid line that was randomly oriented to the second hand of a wristwatch (Figure 2). Plot grid lines were used to measure 1, 10, and 100-hr fuels in 208 cm increments, and 1000-hr fuels were measured throughout the 15.2 m (Figure 2). Two 56-cm radius subplots served as dual-purpose shrub data collection points for acquiring fuel load and total aboveground biomass prediction equation data. Shrub subplots were adjusted to the closest distance relative to original subplot locations [24] to ensure adequate capturing of focal species data. Four 30 × 70 cm plots were used to estimate herbaceous and litter fuel loads, and oven-dried biomass data were extrapolated to per ha basis. Alazan WMA (18.6 ha) contained 15 fuel loading plots, PNPC (21 ha) 16 plots, SFAEF (22.5 ha) 14 plots, SFAEF-Control (21.6 ha) 14 plots, and GWPSR (27 ha) 26 plots.

BehavePlus uses the original 13 and expanded set of 40 fuel models to simulate fire behavior [17,28]. The 53 fuel models have standardized fuel load values based on cover type (grass, shrub, or timber), downed fuel particle size (1-hr, 10-hr, and 100-hr), and live herbaceous and woody fuel load characteristics specific to each cover type. Each fuel model is designed to cover a wide range of fuel conditions (standardized fuel loads per fuel class) specific to each cover type, and does not include species-specific fuel data. However, BehavePlus does have a custom fuel load option that allows the user to adjust fuel loads specific to each fuel classification (e.g., live woody fuel related to shrub fuels).

Research Sites	BA/ha (m^2)	Tree Density (ha^{-1})	Canopy Cover (%)	Dominant Tree Species*** BA/ha (m^2)
Alazan WMA	31.7 (6.2)**	837.2 (257.8)**	78.9 (6.6)**	Sweetgum (11.5)
	(25.2-41.3)*	(467.3-1,254.1)*	(70.0-90.0)*	
PNPC	24.8 (12.3)**	662.0 (491.4)**	82.7 (8.0)**	Mockernut Hickory (6.4)
	(13.8- 48.2)*	(241.3-1,612.1)*	(60-92)*	
G. W. Pirtle Scout Camp	19.3 (6.0)**	426.7 (242.2)**	77.4 (13.3)**	Loblolly Pine (3.8)
	(9.2-32.1)*	(169.5-1,016.0)*	(48-98)*	
SFA Exp. Forest	20.2 (3.7)**	370.3 (165.3)**	75.7 (10.7)**	Loblolly (4.6)
	(18.4-27.5)*	(216.3-682.8)*	(64-96)*	
SFA Exp. Forest -Control	21.3 (4.3)**	394.7 (153.5)**	78.6 (9.2)**	Loblolly (3.7)
	(19.4-29.7)*	(233.6-716.3)*	(65-98)*	

*** Dominant Tree Species=Tree species with the greatest BA/ha (m^2); ** Standard Deviation; * Range

Table 1: Site descriptions using standard, mean overstory cruise metrics for all five sites located in East Texas. Number of plots sampled ranged from 5-12 plots per site depending on stand complexity and total area of the site.

Fuel Type Research Site/ Fuel Model Type	1-Hr *Tonne/Ha (Tons/ac)	10-hr *Tonne/Ha (Tons/ac)	100-hr *Tonne/Ha (Tons/ac)	1000-hr(*S) *Tonne/Ha (Tons/ac)	1000-hr(*R) *Tonne/Ha (Tons/ac)	Herbs *Tonne/Ha (Tons/ac)	Litter *Tonne/Ha (Tons/ac)	Shrubs *Tonne/Ha (Tons/ac)
Alazan Wildlife Management Area	0.10 (0.05)	0.68 (0.30)	0.43 (0.19)	3.89 (1.74)	8.69 (3.88)	*0.37 (0.17)	*3.67 (1.64)	*4.28 (1.91)
Fuel Model 9	5.36 (2.39)	2.51 (1.12)	0.16 (0.07)	6.25 (2.79)	10.08 (4.50)	-	4.15 (1.85)	4.53 (2.02)
Pineywoods Native Plant Center	0.19 (0.08)	2.34 (1.05)	14.23 (6.35)	6.17 (2.75)	8.96 (4.00)	*9.00 (4.01)	*4.36 (1.95)	*2.57 (1.15)
Fuel Model 9	11.34 (5.06)	3.61 (1.61)	0.07 (0.03)	-	0.85 (0.38)	-	3.70 (1.65)	1.43 (0.64)
George W. Pirtle Scout Reservation	0.14 (0.06)	1.23 (0.55)	7.76 (3.45)	16.48 (7.35)	13.98 (6.24)	*7.19 (3.21)	*5.44 (2.43)	*12.33 (5.50)
Fuel Model 7	3.61 (1.61)	2.82 (1.26)	0.31 (0.14)	-	10.11 (4.51)	0.07 (0.03)	5.94 (2.65)	5.18 (2.31)
Stephen F. Austin Exp. Forest	0.14 (0.06)	1.85 (0.83)	8.37 (3.73)	9.05 (4.04)	14.91 (6.65)	*6.51 (2.91)	*6.50 (2.90)	*2.25 (1.00)
Fuel Model 7/2	6.72 (3.00)	2.02 (0.90)	0.36 (0.16)	2.11 (0.94)	0.45 (0.20)	1.32 (0.59)	4.77 (2.13)	3.45 (1.54)
Stephen F. Austin Exp. Forest-Control	0.31 (0.14)	2.19 (0.98)	2.79 (1.24)	21.03 (9.39)	6.44 (2.87)	*0.59 (0.27)	*9.17 (4.09)	*3.17 (1.41)
Fuel Model 11	4.15 (1.83)	5.67 (2.53)	1.03 (0.46)	6.77 (3.02)	1.75 (0.78)	0.43 (0.19)	5.22 (2.33)	0.16 (0.07)

* Tonne=1000 Kg/ha, *S=Solid, *R=Rotten, * Significant differences in Herbs ($p<0.0001$), Litter ($p<0.001$), and Shrubs ($p<0.02$)

Table 2: Mean surface fuel load data for each site compared to fuel load data depicted in the closest representative fuel model in Ref. [11].

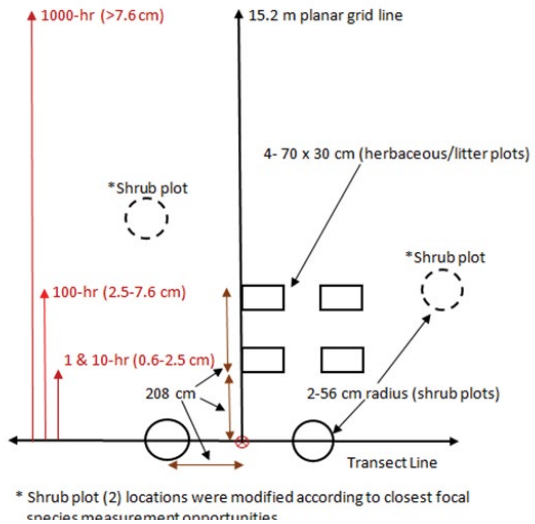

Figure 2: Plot with modified shrub plots that were adjusted at each plot to capture focal species shrub data [24].

For total above ground biomass assessment, entire plant samples (excluding roots) of yaupon, Chinese privet and Chinese tallow were collected in the 56-cm radius fuel loading subplots to estimate shrub fuel loads. Prior to collection, basal diameter and height were measured for use in developing total aboveground biomass prediction equations. A minimum of 10 plant samples of each species were collected throughout each of the sites according to three height classes (0-2, 2-4, and 4-6 m), for a total of 30 samples per site. Height classes not present in subplots were sampled as close as possible to fuel loading plots and shrub subplots at each research site. Dry mass data processing was conducted on the SFASU campus utilizing an air-convection oven. Samples were dried for 48-72 hours at a 110° C until dry mass stabilized, when final mass was measured.

Data analysis

Fuel load data were examined using a Kruskal-Wallis test to determine site differences in fuel loads ($p<0.05$) among understory shrubs, herbaceous cover, and litter fuels. Mean fuel data were simulated in the BehavePlus fire modeling system according to fuel and weather parameters, based on average bad fire days in East Texas, defined as: temperature 65°-70°F, winds 16-24 km/hr, relative humidity 25-35%, 10-hr fuel moisture 10-12%, and 5-10 days since the last significant rain

[14]. BehavePlus fuel model selection was based on representative cover types (53 fuel models). Southern rough (FM-7), low load broadleaf litter (FM-182), moderate broadleaf litter (FM-186), and moderate load, humid climate, timber-shrub (FM-162) fuel models were used in conjunction with the BehavePlus custom fuel load option. Fire behavior simulations were compared among research sites and representative fuel models to determine any change in fire behavior with respect to fuel load variances.

Resulting dry mass, basal diameter and height data were used in simple and multiple regressions to create species-specific, total aboveground biomass prediction equations using SAS 9.2. Total aboveground biomass prediction equations were used for estimating shrub and tree biomass fuel loading indices for inclusion into fire modeling systems [29]. Shrub biomass equations are typically derived from simple regressions utilizing basal diameter as the independent variable, while tree (overstory) biomass equations utilize multiple regression using basal diameter and height as independent variables. Since all focal species were capable of reaching heights that could be considered "tree forming," a multiple regression prediction equation was developed to improve biomass prediction accuracy for larger plants. Total aboveground biomass prediction equations for yaupon, Chinese privet, and Chinese tallow were derived by plotting total-plant dry mass as the dependent variable (Y) and basal diameter (X_1), and height (X_2) as the independent variables utilizing multiple regression. Simple regression included total-plant dry mass (Y) plotted as a function of basal diameter (X). Scatter plot data specific to each species regression model was evaluated with log-transformed data and fit with a linear best fit line to identify the total aboveground biomass equation with the best R-squared value for estimating fuel loading indices for each focal species [29]. Each biomass equation was corrected for log-normal bias (back-transformation correction factor), which is a tendency to under estimate biomass when converting regression prediction equations from logarithmic to arithmetic units. An earlier biomass prediction equation for yaupon [30] was compared with our results.

Results

Forest inventory

The Alazan WMA site was 18.6 ha, with no notable slope or aspect. Species composition consisted of blackgum (*Nyssa sylvatica*), cherrybark oak (*Quercus pagoda*), Chinese tallow, Florida maple (*Acer floridanum*), laurel oak (*Q. laurifolia*), mockernut hickory (*Carya tomentosa*), overcup oak (*Q. lyrata*), red maple (*A. rubrum*), southern red oak (*Q. falcata*), sweetgum (*Liquidambar styraciflua*), and white oak (*Q. alba*) with a mean basal area/ha (BA/ha) of 31.7 m^2 (Table 1). Mean tree density was 837 trees ha^{-1}, with a mean percent canopy cover of 79%. The four dominant tree species based on BA/ha were sweetgum (11.5 m^2), blackgum (5.1 m^2), red maple (3.2 m^2), and Florida maple (3.2 m^2).

The 21.0 ha PNPC site had no notable slope or aspect. Species composition was American elm (*Ulmus americana*), cherrybark oak, Florida maple, green ash (*Fraxinus pennsylvanica*), hop hornbeam (*Ostrya virginiana*), loblolly pine (*Pinus taeda*), mockernut hickory, red maple, southern red oak, sweetgum, sugarberry (*Celtis laevigata*), water hickory (*Carya tomentosa*), and water oak (*Q. nigra*) with a mean BA/ha of 24.8 m^2 (Table 1). Mean tree density was 662 trees ha^{-1}, with a mean percent canopy cover of 83%. The three dominant tree species by BA/ha were mockernut hickory (6.4 m^2), green ash (3.7 m^2), and American elm (2.3 m^2).

The 25 ha GWPSR site varied in aspect (N-SSE) and slope (0-36.4%). Species composition consisted of American elm, black cherry (*Prunus serotina*), blackgum, cherrybark oak, loblolly pine, mockernut hickory, post oak, red maple, shortleaf pine (*P. echinata*), southern red oak, sweetgum, white oak, and winged elm (*Ulmus alata*) with a mean BA/ha of 19.3 m^2 (Table 1), mean tree density was 427 trees ha^{-1}, and a mean percent canopy cover of 77%. The three dominant tree species by BA/ha were loblolly pine (3.8 m^2), post oak (3.6 m^2), and winged elm (3.3 m^2).

The study site at SFAEF consisted of a 21.6 ha area that had aspects ranging from SSE-SSW and slopes varied from 3-10%. Species composition consisted of loblolly pine, longleaf pine (*P. palustris*), shortleaf pine, sweetgum, southern red oak, black oak (*Q. velutina*), cherry bark oak, white oak, hop hornbeam, post oak (*Q. stellata*), and red maple with a mean BA/ha of 20.2 m^2 (Table 1). Mean tree density was 370 trees ha^{-1}, with a mean percent canopy cover of 76%. The three dominant tree species by BA/ha were loblolly pine (4.6 m^2), sweetgum (3.2 m^2), and southern red oak (2.9 m^2).

The SFAEF-C site of 22.5 ha had aspects ranging from NNW-SSW and slopes varied from 7-21%. Species composition consisted of blackgum, black oak, black walnut (*Juglans nigra*), cherrybark oak, hop hornbeam, loblolly pine, longleaf pine, shortleaf pine, post oak, red maple, southern red oak, sweetgum, water oak, and white oak with a mean BA/ha of 21.3 m^2 (Table 1). Mean tree density was 395 trees ha^{-1}, with a mean percent canopy cover of 79%. The three dominant tree species by BA/ha were loblolly pine (3.7 m^2), white oak (3.6 m^2), and sweetgum (3.4 m^2).

Understory fuel load assessment and fire behavior prediction

Fuel loading indices differed considerably across the sites, with the lowest total fuel load at Alazan WMA and the greatest total fuel load at GWPSR (Table 2). The Kruskal-Wallis Test confirmed significant fuel loading variability among the herbaceous ($p<0.0001$), litter ($p<0.001$), and shrub ($p<0.02$) fuel components for all research sites. Alazan WMA consistently had the lowest fuel load indices in the herbaceous, litter, and 1 to 1000-hr (solid) fuel categories, with differences ranging from 208 to 17,145 kg/ha when compared to the greatest fuel loads (Table 2). The SFAEF had the lowest shrub fuel load, with a difference of 10,081 kg/ha when compared to the greatest shrub fuel load at the GWPSR site. Alazan WMA had the lowest combined fuel load totals, likely attributed to frequent inundation of flood waters associated with bottomland hardwood systems. Alazan WMA's largest fuel load components came from downed rotten 1000-hr fuels and shrub fuels (Table 2). Considerable differences in 1-hr, 10-hr, 1000-hr (solid), and herbaceous fuels were observed when Alazan WMA was compared to [14].

Alazan WMA's fire behavior predictions calculated in BehavePlus 5.0 used the most representative fuel model template (low load broadleaf litter fuel model (182) for both the research site and East Texas fuel model. Fuel loading indices for 1-hour, 10-hour, 100-hour, herbaceous, and woody (shrubs) fuels were used in BehavePlus according to Alazan WMA fuel plot data and fuel model type 9. Mean East Texas fire weather and fuel conditions described in [14] were kept constant in all BehavePlus simulations to maintain consistency among predicted behavior indices: midflame wind speed-24.14 km/hr, relative humidity-35%, dead fuel moisture-12%, live fuel moisture-40%, and slope-0%. Previous estimates [14] with BehavePlus fire behavior outputs for rate of spread (ROS), fireline intensity (FI), and flame length (FL) yielded low values for Alazan WMA (Table 3), although Alazan

WMA exhibited slightly higher fire behavior values. Differences in fire behavior outputs were ROS-0.9 m/min, FI-136 kW/m, and FL-0.2 m. Low fire behavior outputs for both sites were expected due to lower fuel loading indices, decreased flammability of hardwood litter, and lack of herbaceous fuels.

The PNPC yielded the greatest combined fuel loading indices for the hardwood-dominated ecosystems. When compared to Alazan WMA, PNPC downed woody fuel accumulations were considerably greater in the 10-hr, 100-hr, and solid 1000-hr categories (Table 2). Greater herbaceous densities were also associated with the PNPC. Increased fuel loading in all categories at the PNPC site could be explained by fewer flooding events compared to Alazan WMA. Fewer inundation events would allow more herbaceous growth and slow decomposition rates in downed woody fuels. The comparable fuel model previously described [14] had greater 1-hr fuel loads and substantially lower 100-hr, solid and rotten 1000-hr, and herbaceous fuel loads.

Fire behavior predictions for the PNPC were calculated by using the moderate load broadleaf litter fuel model (186). Fuel loading indices were from the PNPC fuel plot data and the most representative fuel model type 9. Fire behavior outputs produced more intense fire behavior outputs for PNPC fuel loads in ROS, FI, and FL when compared to [14] model (Table 3). Increased fire behavior outputs at the PNPC could be explained by greater accumulations of 1 and 10-hr fuels combined with a twenty-three-fold increase in herbaceous fuels. Whereas, Alazan WMA has more frequent flooding combined with greater shrub fuel loads that will tend to suppress flashy herbaceous fuels that carry fire, and when combined with heavy accumulations of large diameter downed fuels, fire spread will dramatically decrease. Fire behavior outputs produced more intense fire behavior outputs for [11] model in ROS, FI, and FL when compared to the PNPC fuel loads (Table 3). Decreased fire behavior outputs could be explained by greater accumulations of 100 and 1000-hr fuels combined with a six-fold increase in shrub fuels. An abundance of shrub fuels, combined with hardwood litter, will tend to suppress flashy herbaceous fuels that carry fire, and when combined with heavy accumulations of large diameter downed fuels, fire spread will dramatically decrease.

The GWPSR had the greatest shrub and total combined fuel load of all five sites. When compared to the other two pine-dominated ecosystems, GWPSR had an ~ six-fold increase in yaupon-dominated shrub cover than SFAEF and an ~ four-fold increase than SFAEF-C (Tables 4 and 5). Greater yaupon density at the GWPSR site is most likely attributed to a combination of past silvicultural practices and the current passive management regime. Overstory tree mortality resulting from the 2011 drought may have also exacerbated yaupon growth through greater light availability derived from greater occurrences of gap openings in the overstory canopy.

	Fire Behavior Rating		
Site and Fuel Model	**ROS (m/min)**	**FI (kW/m)**	**FL (m)**
Alazan WMA *(BP FM-182)	4.6	464	1.3
Fuel Model Type 9	3.7	328	1.1
Pineywoods Native Plant Center *(BP FM-186)	14.6	3908	3.5
Fuel Model Type 9	7.8	779	1.7
G.W. Pirtle Scout Reservation *(BP FM-7)	44.4	25,010	8.2
Fuel Model Type 7	88.7	25,908	8.3
SFA Exp. Forest *(BP FM-7)	55.3	22,915	7.8
Fuel Model Type 7/2	88.8	20,981	7.5
SFA Exp. Forest-Control *(BP FM-162)	38.6	11,463	5.7
Fuel Model Type 11	28.8	3,813	3.4

*Comparable BehavePlus fire model numbers (BP FM-XX) were used as general templates for comparison. Fuel loading data specific to the research site and representative [11] fuel models were used in the general BehavePlus templates to generate the resulting fire behavior outputs. Fire weather and fuel conditions were kept constant: Midflame Wind Speed-24 km/hr, Dead Fuel Moisture-12%, Live Fuel Moisture-40%, and slope-0%.

Table 3: Fire behavior ratings for rate of spread (ROS), fireline intensity (FI), and flame length (FL) calculated with BehavePlus 5.0, comparing fuel loads to the most representative fuel model in Ref. [11].

Site Metrics **Site and Species**	**Tonne/Ha** **(Tons/ac)**	**Mean** **% Cover**	**Mean** **Sample (n)**	**Range**	**Standard Deviation**
G.W. Pirtle Scout Reservation SFA Experimental Forest *I. vomitoria* (yaupon) Aboveground biomass (g) Height (m) Basal diameter (cm)	 11.88 (5.30) 1.70 (0.76)	 96.31 75.52	 1,071.1 (32) 2.2 1.7	 0.4 – 11,333.9 0.2 – 5.8 0.1 – 6.8	 2,619.2 1.8 1.7
Pineywoods Native Plant Center *L. sinense* (Chinese privet) Aboveground biomass (g) Height (m) Basal diameter (cm)	 1.96 (0.87)	 76.24	 1,373.9 (27) 2.9 2.4	 0.2 – 9,119.3 0.2 – 5.9 0.1 – 6.3	 2,142.6 1.8 1.9
Alazan WMA *T. sebifera* (Chinese tallow) Aboveground biomass (g) Height (m) Basal diameter (cm)	 3.10 (1.38)	 72.52	 1,525.6 (27) 3.4 3.9	 45.7 – 4,321.7 0.7 – 6.0 1.2 – 7.6	 1,408.9 1.8 1.8

Table 4: Invasive species weight per hectare and acre, and mean percent cover estimated at G.W. Pirtle Scout Reservation, Stephen F. Austin Experimental Forest, Pineywoods Native Plant Center, and Alazan WMA research sites. Mean height, basal diameter, and total aboveground biomass data for yaupon, Chinese privet, and Chinese tallow collected from corresponding research sites.

Site Metrics Research Site	Total Shrub WeightTonne/Ha (Tons/ac)	Invasive Shrub WeightTonne/Ha (Tons/ac)	% Invasive shrub Cover (Ha/ac)
G.W. Pirtle Scout Reservation	12.33 (5.50)	11.88 (5.30)	96.31
SFA Experimental Forest	2.25 (1.00)	1.70 (0.76)	75.52
Pineywoods Native Plant Center	2.57 (1.15)	1.96 (0.87)	76.24
Alazan WMA	4.28 (1.91)	3.10 (1.38)	72.52
SFA Experimental Forest Control	3.17 (1.41)	-	-

Table 5: Comparison of invasive shrub percent cover, and estimated total shrub and invasive shrub weights from perspective research sites.

Fire behavior predictions for the GWPSR were calculated using the southern rough fuel model (007) for both research site and fuel model type. Fuel loading indices were from the GWPSR fuel plot data and the most representative fuel model type 7. Comparison of BehavePlus fire behavior predictions produced higher ROS, FI, and FL indices for [14] when compared to GWPSR fuel loads (Table 3). Outputs produced the second greatest ROS, and the greatest FI, and FL when compared to all sites. Substantially higher outputs were expected for the GWPSR due to high yaupon densities. However, the contribution of heavy accumulations of shrubs may have slowed the ROS considerably by increasing fuel load compactness through dense spatial arrangements of heavier woody fuels (10-100-hr live fuels) when compared to other sites. Comparison of GWPSR and [14] fuel loads revealed substantial increases in 1-hr and 10-hr fuels and significant decreases in 1000-hr sound, 1000-hr rotten, and shrub fuels. Consequently, the significant increase in lighter fuels and decrease in heavy fuels produced a 44.3 m/min increase in ROS, an 898 kW/m decrease in FI, and a 0.1 m decrease in FL in BehavePlus. However, BehavePlus fire behavior data for both the GWPSR site and [11] indicate high FI and FL indices at both sites with a two-fold increase in ROS associated with [14].

The SFAEF site had the second largest combined fuel loading among the three pine-dominated sites. Downed woody fuel loads were similar across pine-dominated sites, with the exception of a 5,578 Kg/ha difference in 100-hr fuel loads between the SFAEF and SFAEF-C site. The SFAEF site exhibited the lowest shrub fuel load of the three sites, while maintaining moderately high herbaceous and litter fuel loads. Differences in shrub and herbaceous fuel loads when compared to the GWPSR site were most likely attributed to a departure from intensive silviculture practices.

Fire behavior predictions for the SFAEF were generated using the southern rough fuel model (007). Fuel loading indices were from the fuel plot data and the most representative East Texas fuel model type (7/2). Comparison of fire behavior predictions yielded a greater ROS for fuel model type 7/2 and greater FI and FL indices for the SFAEF. The SFAEF BehavePlus output for ROS (55.3 m/min) ranked highest among pine-dominated, while FI (22,915 kW/m) and FL (7.8 m) indices ranked second highest, and [14] exhibited higher 1-hr and shrub fuels, and lower 100-hr, sound and rotten 1000-hr, herbaceous, and litter fuels when compared to the SFAEF site. Subsequent results yielded a greater ROS of 33.5 m/min in [14], while the SFAEF site produced greater FI and FL indices. ROS comparisons among pine-dominated sites and [14] continue to follow a similar trend of increasing ROS's with concomitant reductions in heavier fuels (shrub and 100-1000-hr) and increases in lighter fuels (herbaceous, litter, and 1-10-hr). FI and FL indices appeared to be influenced by a combination of greater fuel load values in the 1-hr, 10-hr, herbaceous, litter, and shrub categories.

The SFAEF-C site had the lowest combined fuel loading among the 3 pine-dominated sites. The SFAEF-C site exhibited a decrease in 100-hr and herbaceous fuels, and an increase in litter fuel when compared to other pine-dominated sites. Shrub fuel loads at the SFAEF-C site were moderate at 3,166 kg/ha. Fuel load comparisons between the SFAEF-C site and [14] indicated considerable variation among all fuel categories. Variances in herbaceous and litter fuel loads when compared to the SFAEF site were attributed to greater litter accumulations resulting from a greater BA/ha and tree density combined with a greater presence of hardwoods in the overstory. Subsequent increases in hardwood litter and pine needle cast appeared to be effective in suppressing herbaceous growth. Fire behavior predictions for the SFAEF-C were generated using the moderate load, humid climate, timber-shrub fuel model (162). Fuel loading indices were from the SFAEF-C fuel plot data and the most representative fuel model type (11). Comparison of fire behavior predictions yielded greater ROS, FI, and FL indices for the SFAEF-C research site when compared to previous work [14], and produced the lowest ROS, FI, and FL indices when compared against all pine-dominated research sites. Decreased herbaceous fuels and increased litter fuels appeared to have the greatest effect on the low ROS associated with the SFAEF-C site, while decreased herbaceous and 100-hr fuels appeared to have influenced the lower FI and FL indices when compared to all pine-dominated sites. Consequently, the resulting output reported in [14] were considerably lower in ROS, FI, and FL indices when compared to the SFAEF-C site.

Total aboveground biomass

Thirty-two whole-plant samples of yaupon with a wide range of height, basal diameter, and dry biomass metrics were collected (Tables 4 and 5). Multiple and simple regression used log-transformed basal diameter (cm) and height (m) data to produce equations with a log-normal bias correction factor. The multiple regression successfully explained 98% of the variance in diameter and height (Table 6), and the simple regression also performed well, explaining 96% of the variance in diameter alone (Table 7). Previous total aboveground prediction equations [30] used a simple regression prediction equation for yaupon in east Texas, utilizing a 30-plant sample ranging from 6-20 mm basal diameter and 14.5-432.5 g dry biomass (r^2=0.88). The new multiple and simple regression equations were compared to [27] prediction equation by plotting a series of basal diameters from 5-60 mm in 5 mm increments (Figures 3 and 4), and revealed a very similar prediction trend, while the simple regression equation varied by roughly 100 g in the 5-30 mm range and 500-3000 g in the 30-60 mm range. The new simple regression equation was then used for processing shrub level fuel plot calculations due to an accuracy improvement based on a wider sample range of basal diameters, and a greater r^2 value (0.96 compared to 0.88) compared to [30].

Multiple and simple regression data for Chinese privet (n=27) were similar to yaupon with a wide range of height, basal diameter, and dry biomass data. The simple and multiple regressions both explained 98% of the Since both multiple and simple regression prediction equations performed well, Chinese privet fuel calculations were processed with the new simple regression prediction equation (Table 7). Multiple and simple regression data for Chinese tallow (n=27) also had a wide range of height, basal diameter, and dry biomass categories. Multiple regression explained 97% of the variance, while the simple regression explained 96% therefore, all calculations were processed with the new simple regression equation (Table 7).

Species	Prediction equation (corrected)	r^2	MSE	CF
I. vomitoria (yaupon)	$Y=39.09169D^{1.83881}H^{1.02427} \times 1.04914$	0.98	0.30	1.04
L. sinense (Chinese privet)	$Y=40.87628D^{2.02783}H^{0.75376} \times 1.04706$	0.98	0.30	1.04
T. sebifera (Chinese tallow)	$Y=31.49698D^{2.09924}H^{0.52966} \times 1.02547$	0.97	0.22	1.02

D=diameter (cm), *H*=height (m), and Y=total aboveground biomass (g). Log-normal bias correction was calculated using $CF=e^{MSE/2}$, where MSE equals mean square error.

Table 6: Final log-transformed multiple regression equations for total aboveground biomass of yaupon, Chinese privet, and Chinese tallow collected in East Texas.

Species	Prediction equation (corrected)	r^2	MSE	CF
I. vomitoria (yaupon)	$Y=53.72293D^{2.81233} \times 1.12015$	0.96	0.47	1.12
L. sinense (Chinese privet)	$Y=54.17502D^{2.66992} \times 1.06487$	0.98	0.35	1.06
T. sebifera (Chinese tallow)	$Y=25.20116D^{2.71203} \times 1.03810$	0.96	0.27	1.03

D=diameter (cm) and Y=Total aboveground biomass (g). Log-normal bias correction was calculated using $CF=e^{MSE/2}$, where MSE equals mean square error.

Table 7: Final log-transformed simple regression equations for total aboveground biomass of yaupon, Chinese privet, and Chinese tallow collected in East Texas.

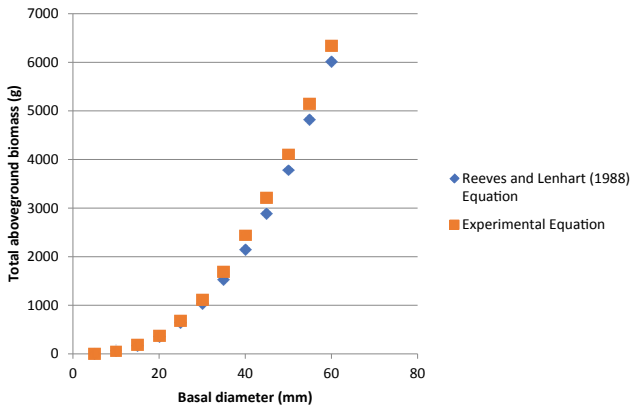

Figure 3: Comparison of multiple regression prediction equations from Reeves and Lenhart and the new equation using 5-60 mm basal diameters in 5 mm increments.

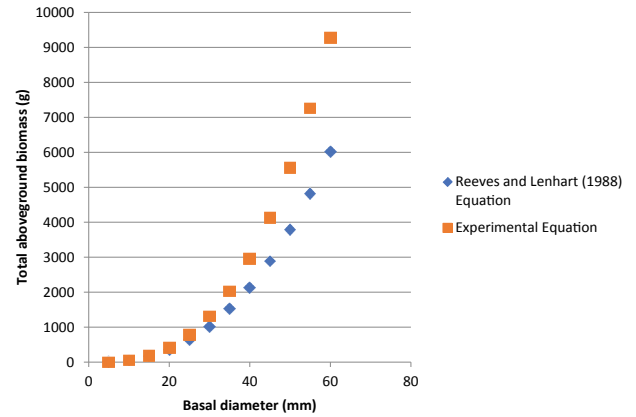

Figure 4: Comparison of simple regression prediction equations from Reeves and Lenhart and the new equation using 5-60 mm basal diameters in 5 mm increments.

Discussion

Differences in fuel loads between our results and [14] indicate a clear need to update fuel loading indices in regional fuel models. Increases in downed woody fuel loads were most likely attributed to recent drought events (2011), combined with a concomitant increase in tree mortality [28-31]. Variances in downed woody fuel (1-hr to 1000-hr fuels) accumulations were most likely influenced by a number of factors, including decomposition rates (mesic vs. xeric sites), overstory age, drought stress, fire exclusion, and passive management regimes [3,17,32-36]. Shrub, herbaceous, and litter fuel loads probably varied due to forest ecosystem type, overstory composition, canopy closure, past management regimes, fire exclusion, and current passive management practices [3,17,35-37]. Consequently, high understory fuel loads exist within the East Texas region, which presents unique problems for fire managers involved with prescribed burning, fuels management, and wildfire risk assessments within the WUI.

Comparison of our hardwood fuel data and [14] indicated differences in fuel loads among all hardwood systems, and fire behavior outputs differed slightly at Alazan WMA, but were significantly greater at the PNPC due to increased herbaceous and 1 and 10-hr fuels, especially herbaceous fuels. remained relatively low, which is consistent with many hardwood ecosystems [3,34]. Pine-dominated sites exhibited a trend of increasing surface fuel loads when compared to [14]. Fire behavior outputs were consistent in FI and FL based on overall increasing fuel loads, while ROS appeared to trend slower with increasing density of shrub and litter fuels with a concomitant decrease in herbaceous fuels. Primary differences in fire behavior appear related to a significant increase in downed woody 1-hr and shrub fuels with a decrease in herbaceous fuels. Decreasing herbaceous fuel is consistent with increasing shrub density and becomes more pronounced as understory cover increases [3,17,37]. As invasive shrubs continue to increase in understory fuel strata in east Texas, fire frequency will likely decrease relative to historic FRI's, and the probability of greater fire severity will increase with greater shrub densities. Prioritization of updated fuel loading indices for regional fuel models should focus on fire-prone, upland ecosystems where the benefits of prescribed burning and fuels mitigation projects targeting high-risk WUI areas could achieve maximum effectiveness.

High understory fuel loading of downed woody and shrub fuels can increase fire severity under severe drought and weather conditions [3,9,38,39]; while normal precipitation and average weather conditions can decrease ignitability and combustibility during optimal times for prescribed burning [9,13,34,40,41]. Mechanical and herbicide treatments are often necessary prior to reintroducing cost effective prescribed burning regimes to increase prescribed burn effectiveness and reduce the potential for high fire intensity and damages associated with wildfires [3,38]. Landowners residing within the WUI are encouraged to use fire resistant plants for landscaping, while avoiding known flammable species containing volatile oils, which include pines (*Pinus* spp.), yaupon, and gallberry [20,21,41]. An estimated 10 million Texas residents live in the WUI [32], prompting the need for more accurate wildfire risk assessment tools. Improved fire behavior predictions facilitated by updated regional fuel models could greatly

improve these efforts; therefore, prioritization for updating fuel loading indices for regional fuel models should focus on fire-prone, upland ecosystems where the benefits of prescribed burning and fuels mitigation projects targeting high risk WUI areas could achieve maximum effectiveness.

Accurately estimating woody shrub biomass is a valuable component for updating and creating new fuel loading indices for regional fuel models. Earlier work [27,30] demonstrated the utility of creating multiple and simple linear regression equations to estimate total aboveground and/or crown biomass for shrubs and small trees to aid with fuel loading estimation. The importance of creating fuel weight prediction equations specific to East Texas has been noted [14]. This study added two common East Texas exotic invasive species (Chinese privet and tallow) total aboveground biomass prediction equations to existing knowledge and reaffirmed past [14] biomass prediction equation for yaupon with a wider range of basal diameters.

Simple and multiple regression equation results were consistent with prior studies [24,26,27] and are useable prediction equations for Chinese privet and tallow total aboveground biomass estimations within East Texas. Multiple regression equations appear to be slightly more accurate based on slightly greater r^2 values when compared to simple regression equations, but modest increases in r^2 value accuracy might not be worth the added labor and cost associated with collecting extra height data. Due to over estimation discrepancies with the new yaupon simple regression equation, it may be advisable to use the past equation [14] for estimating small basal diameter (0.6-2.0 cm) yaupon, while the new equation could be used to estimate larger basal diameter (2.0-6.8 cm) yaupon.

Conclusions

Considerable variation in East Texas fuel model data exist, and updated fuel loading indices will increase fire behavior prediction accuracy. Fire exclusion, passive management, and drought-related tree mortality appear to be the primary factors contributing to greater shrub densities and downed woody fuel loads in regional forest understories. Greater shrub and downed woody fuel densities can increase FI and FL indices leading to greater fire intensity and severity. The creation of these new biomass prediction equations should assist fire mangers estimates of understory shrub fuel loadings, and with the resulting greater accuracy in fire behavior prediction, improve fire managers' ability to conduct effective prescribed burns, identify high-risk WUI areas, and enhance wildfire operations and planning objectives.

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