1E.4 SEASONAL CHANGES IN SELECTED COMBUSTION CHARACTERISTICS OF ORNAMENTAL VEGETATION

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ABSTRACT

Flammability of living vegetation is influenced by a variety of factors including moisture content, physical structure and chemical composition. The flammability of ornamental vegetation is of interest to homeowners seeking to make their homes "fire-safe". The relative importance of the factors influencing flammability is unknown. We measured the peak heat release rate, mass loss rate, time to ignition, and effective heat of combustion of 100 mm x 100 mm samples of foliage and small branches using a cone calorimeter. Green and oven-dried samples of 10 species were collected and tested seasonally for a period of 1 year. Similar measurements were made on whole shrubs in a large combustion facility. Results of these tests will be presented.

1. INTRODUCTION

Wildland fire has affected the wildland-urban interface (WUI) for decades. In the past, most of the interface fires occurred in southern California in chaparral. However, as the U.S. population has moved and wildland fire occurrence has been altered, WUI fires now occur in a majority of states. The U.S. National Fire Plan recognized and is addressing this problem through activities such as hazardous fuels reduction and support of the FIREWISE program.

One component of the FIREWISE program involves landscape design and selection of plants that are desirable. People choose landscaping plants for a variety of reasons that may be mutually exclusive. For instance, a plant may be very desirable because it is highly drought resistant; however, the drought resistant characteristics may make the plant highly flammable.

Plant inflammability has been examined over the past few decades. Different plant characteristics have been used to define flammability. Radtke (1978) described 66 years of work by forestry and fire officials in Los Angeles County, California to plant native and exotic species in and adjacent to chaparral to provide fire protection and erosion control. Work to identify slow-burning plants that could survive in southern California began in the 1950s and plants with high mineral content were identified as fire-retardant plants (Ching and Stewart 1962). In another study, low flammability was defined to mean low fuel volume and several species were identified (Nord and Green 1977).

Vegetation moisture content and plant geometry are two of the most critical determinants of flammability. Both the size of a plant's foliage and branches, expressed as the surface area to volume ratio σ, and the proximity of foliage and branches are important factors governing flammability. Other components include the presence or absence of volatile compounds that may contribute to ignition and combustion processes.

Dimitrakopoulos (2001) provided a current summary of the status of vegetation flammability rating in Europe and the U.S. There is no universally accepted method of flammability rating for vegetation. We have investigated the potential use of the cone calorimeter to devise a flammability rating for vegetation (White et al 1996, White et al 1998). The samples we tested with the cone calorimeter were small (100 *mm* x 100 *mm*) and composed of principally foliage and fine branches < 0.64 *cm*. We don't know how these small-scale measures relate to measurements of combustion properties of larger plants

Wildland vegetation typically exhibits an annual cycle of moisture content (eg., Weise et al. 1998). In southern California, woody chaparral species increase their moisture content during the winter and spring months during the rainy season. The moisture content generally decreases during the long, often rainless, summer and fall. While it is true that these fuels are less flammable during periods when moisture content is high, we don't have good quantitative measures of the various combustion properties for wildland species, nor do we know how the properties change as the plants grow throughout the year.

In this paper we examine the seasonal differences in combustion characteristics between several species used for landscaping in southern California. We also tested agreement between small-scale tests made with a cone calorimeter and larger-scale tests made in a large test facility.

2. METHODS

Two sets of flammability tests were performed in 1996 and 1997 on a variety of ornamental plant species found in southern California. The 1st experiment examined the seasonal changes in peak heat release rate, effective heat of combustion, and time to ignition for 10 different species.

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Measurements were made on both green (moist) and oven-dry samples. A randomized complete block design was used. The testing order was randomly determined within a block and three blocks were tested in each of 4 months for both oven-dry and moist samples. A total of 240 samples 100 mm x 100 mm in size were tested at the Forest Service Forest Products Laboratory (FPL) in Madison, WI.

The 2nd experiment examined the correlation between heat release rate and effective heat of combustion measured by a cone calorimeter and an intermediate scale biomass calorimeter. Five species were selected for testing. Two or three replicates of each species were burned in the Intermediate Scale Biomass Calorimeter located at the University of California Forest Products Lab (UCFPL). A replicate consisted of 3 to 4 potted plants. Physical characteristics were determined for each species. Three small samples were collected from the larger plants and shipped to FPL for cone calorimeter testing.

2.1 *Materials*

In the series of tests on 10 species, the samples came from the following species: chamise (*Adenostoma fasciculatum* H. & A., CHAM), aloe (*Aloe sp*., ALOE), saltbush (*Atriplex halimus* L., ATRI), wild lilac (*Ceanothus* "Joyce Coulter", CEAN), crimson-spot rockrose (*Cistus ladanifer* L., CILA), sageleaf rockrose (*Cistus salviifolius* L., CISA), toyon (*Heteromeles arbutifolia* M. Roem., TOYO), prostrate myoporum (*Myoporum parvifoliu*m "Putah Creek", MYOP), olive (*Olea europaea* L., OLIV), spiny saltbush (*Rhagodia spinescens,* RHAG). Samples of the plants were obtained by the USDA Forest Service Forest Fire Laboratory in Riverside, California, and were shipped overnight to FPL. The green and dried branch samples with intact foliage were collected from the outer crown of each species with new growth, flowering, and fruiting portions removed. Diameters of the branch samples were $\leq$ 6 *mm*. The plastic bags of 259 green samples were kept in cold storage until testing to retain moisture content. Desiccant was added to the plastic bags with the dried samples.

2.2 *Small-scale test equipment*

The cone calorimeter obtains the heat release rate by measuring the consumption of oxygen as a result of combustion (Huggett 1980, Babrauskus 1984). An electric cone heater exposes the 100 by 100 mm specimen holder to affixed heat flux in an open environment. In these tests, the plant specimens were placed in an aluminum foil container that was laid on a holder with a low-density ceramic wool blanket. To contain the pieces of the specimens, we placed a steel edge retainer frame with a grid over the holder. With the edge frame, the exposed surface area was 0.008836 m^2. This horizontally oriented holder. In these tests, we used a water-cooled shutter to shield the specimen until the test was initiated. An electric spark igniter provided the ignition source. The cone calorimeter at FPL is an Atlas Electric Devices Company CONE2 AutoCal Combustion Analysis System[*] (Fig. 1).

Figure 1. Cone calorimeter located at USDA Forest Service Forest Products Laboratory used to measure combustion characteristics of various vegetation specimens.

Combustion gases were collected in an exhaust hood and duct. Samples of the gases were analyzed for their oxygen, carbon dioxide, and carbon monoxide contents. From these gas concentration measurements, the heat release as a result of combustion was calculated. Initial test data were curves of heat release rate versus time and curves of mass loss rate versus time. Heat release rate is normally expressed as *kW* per exposed surface area (m^2). From the visual observations and these initial test data, results that can be reported included the following: peak heat release rate (PHRR) at time x, average heat release rate over interval y minutes after ignition, total heat release, average mass loss rate, time for sustained ignition, effective heat of combustion versus time, and average effective heat of combustion. Effective heat of combustion (AHOC) is heat release per unit mass loss and includes moisture loss.

2.3 *Intermediate-scale tests*

Intermediate-scale tests were conducted at UCFPL. Five species were tested: big saltbush (*Atriplex lentiformis*), Santa Barbara ceanothus (*Ceanothus impressus* 'Eleanor Taylor'), sageleaf rockrose (*Cistus salviifolius*), spiny saltbush (*Rhagodia spinescens*), and rosemary (*Rosmarinus officinalis* 'prostrata'). An Intermediate Scale Biomass Calorimeter was constructed to measure release rate and combustion efficiency using oxygen depletion calorimetry (ODC). It consisted of equipment to measure CO and CO_2, two platform load cells, a propane line burner, a three- sided ceramic board enclosure, a plant rack, and a data acquisition system.

The oxygen depletion calorimeter samples exhausted gases that rose through the hood from the burning plants. The oxygen concentration was measured in the hood and compared to the normal ambient concentration determined prior to ignition. A three-sided wooden wall, lined with ceramic fiber

[*] The use of trade names is provided for information purposes only and does not constitute endorsement by the U.S. Department of Agriculture.

board, surrounded the plant rack and line burner (see Fig. 2).

To produce an even heat output from the propane burner, propane gas was uniformly forced through a 15 cm tall column of sand. This sand propane burner put out a wall of flame about 1 meter in length. The flame leaned into the fuel bed at an angle of about 45° due to entrainment of air caused by the surrounding walls. This allowed the entire width of the vegetation to be penetrated with flame. Depending on the height and depth of the vegetation, the flame mainly penetrated the middle of the fuel in a vertical orientation and missed the back bottom and top front of the fuel. Convection, radiation, and intermittent flame contact heated those areas missed by continuous flame impingement.

Figure 2. Intermediate scale biomass calorimeter at University of California Forest Products Laboratory used to measure combustion characteristics of small shrubs using oxygen consumption calorimetry.

2.4 *Procedures*

Cone calorimeter samples were removed from the plastic bags, weighed, and placed in the holder immediately prior to testing. The amount of material was usually a single layer of foliage with the entire exposed surface area of the sample holder not covered. A radiant flux of 25 $kW\ m^{-2}$ was used to ignite the samples. Gas concentration and mass loss measurements were sampled at 1 *hz*. A small orifice plate was used in the exhaust duct to obtain a measured exhaust flow of 0.012 $m^3\ s^{-1}$.

Intermediate scale samples were prepared by placing 1-4 plants on the plant rack at the UC Forest Products Lab. In order to maintain moisture, the plants were kept potted and watered regularly until tested. Because the samples consisted of complete plants, several plants were cut up to determine mass distribution, particle density, surface area to volume ratio, and foliage volatile percentage for each species. Leaf samples were taken from five individuals of each species for gas chromatograph analysis to determine the volatile percentage. The remaining plants were used in the calorimeter tests. PHRR ($kW\ m^{-2}$) and energy output (*MJ*) were determined. PHRR was normalized using crown area of the shrubs and AHOC was calculated using eq. 1.

$$AHOC = \frac{\text{Total energy output}}{mass(1 + mc/100)} \qquad (1)$$

where *mass* is oven-dry mass and *mc* is oven-dry moisture content (%).

2.5 *Statistical analysis*

PHRR was normalized on a per unit area basis: the sample holder area was used for the cone calorimeter and estimated crown area was used for the intermediate scale tests. Analysis of variance was used to test the effects of species and season on PHRR and AHOC. PHRR for oven-dry and green samples was ranked separately within a season. Ranks for oven-dry and green samples were compared to determine if moisture content changed the species order.

Due to the limited size of the intermediate scale tests, only plots and correlation were used to determine if a relationship existed between the cone calorimeter and the intermediate scale biomass calorimeter results. Both PHRR and AHOC were examined.

3. RESULTS

Moisture content of some species such as chamise changed appreciably over the test period (Fig. 3). Aloe and myoporum, both succulent species, maintained moisture contents > 400% for the entire experiment. All species except chamise were located in a commercial nursery and watered regularly. Chamise was located adjacent to the nursery and only received rainfall. The surface area to volume ratio (σ) was similar for the 10 species with the exception of aloe (Table 1). While the branch σ for most species were similar, there was a wider range in leaf σ. The composite σ for aloe was lowest and highest for the *Rhagodia*.

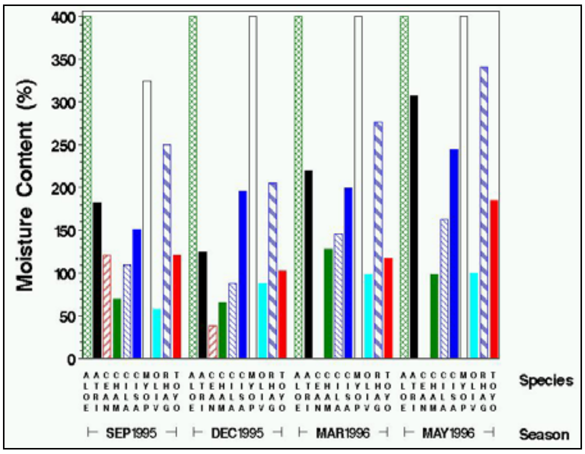

Figure 3. Mean moisture content of foliage samples from 10 ornamental plant species tested using a cone calorimeter.

3.1 *Cone Calorimeter Tests*

PHRR was appreciably different between green and oven-dry samples (Table 2). Green samples exhibited lower PHRR. PHRR for oven-dry samples ranged from 285 $kW\ m^{-2}$ (olive) to 63 $kW\ m^{-2}$ (aloe). Range of PHRR for green samples was 1 – 165 $kW\ m^{-2}$. AHOC for green samples was also lower than AHOC for oven-dry samples. The range in AHOC was smaller than for PHRR : 9.3 – 22.3 $MJ\ kg^{-1}$ for oven-dry samples, 0.2 – 10.6 $MJ\ kg^{-1}$ for green samples. In some instances, the green samples did not sustain ignition with the 25 $kW\ m^{-2}$ radiant ignition flux.

Table 1. Estimated surface area to volume ratios for ornamental plant species in California.

Species	Surface area/Volume (σ, cm^{-1})		
	Leaf	Branch	Composite
Aloe sp. (ALOE)	7.3	5.6	5.0
Atriplex halimus (ATRI)	37.3	15.0	33.4
Ceanothus “Joyce Coulter” (CEAN)	44.0	13.0	34.3
Adenostoma fasciculatum (CHAM)	42.3	14.7	30.2
Cistus landanifer (CILA)	40.4	22.2	39.3
Cistus salvifolius (CISA)	36.5	26.3	35.8
Myoporum parvifolium (MYOP)	19.7	9.9	17.2
Olea europaea (OLIV)	55.9	21.2	42.9
Rhagodia spinescens (RHAG)	75.3	22.1	60.9
Heteromeles arbutifolia (TOYO)	26.5	8.9	23.0

As can be seen in Table 2, we observed differences in PHRR and AHOC between species. Analysis of variance of the oven-dry vegetation indicated that season, species, and species-season interaction affected PHRR; season and species significantly affected mean AHOC (significant defined as $\alpha \leq 0.05$). Species, season, and their interaction affected PHRR and AHOC for green samples.

It was not possible to isolate the effects of species and season individually on PHRR or AHOC because of the presence of interaction. The changes in PHRR and AHOC can be seen in Fig. 4 and 5 for oven-dry and green vegetation, respectively. For many of the species, there is a suggestion of a seasonal trend in PHRR. For the oven-dry samples, PHRR appears to have increased for samples tested in December and March. A similar trend was observed for the green samples, particularly olive, chamise, and myoporum. As noted above, the range in AHOC was small compared to the range of measured PHRR. For olive, the AHOC of oven-dry vegetation was similar for the 4 sampling times. Other species exhibited a slight trend with higher AHOC occurring in December and March. Mean PHRR was ranked from highest to lowest for oven-dry and green samples separately for each group of seasonal tests. Ranks were evaluated to determine if the relative order of species changed. The two species with highest PHRR (and lowest rank) were chamise and olive (Table 3). Aloe consistently had the highest ranks and lowest PHRR. The relative position of both *Rhagodia* and *Atriplex* changed between the August 1995 and December 1995 sampling periods. The PHRR for these two species increased relative to the other species examined. The ranks of the species other than chamise, olive, and aloe changed over the course of the sampling period

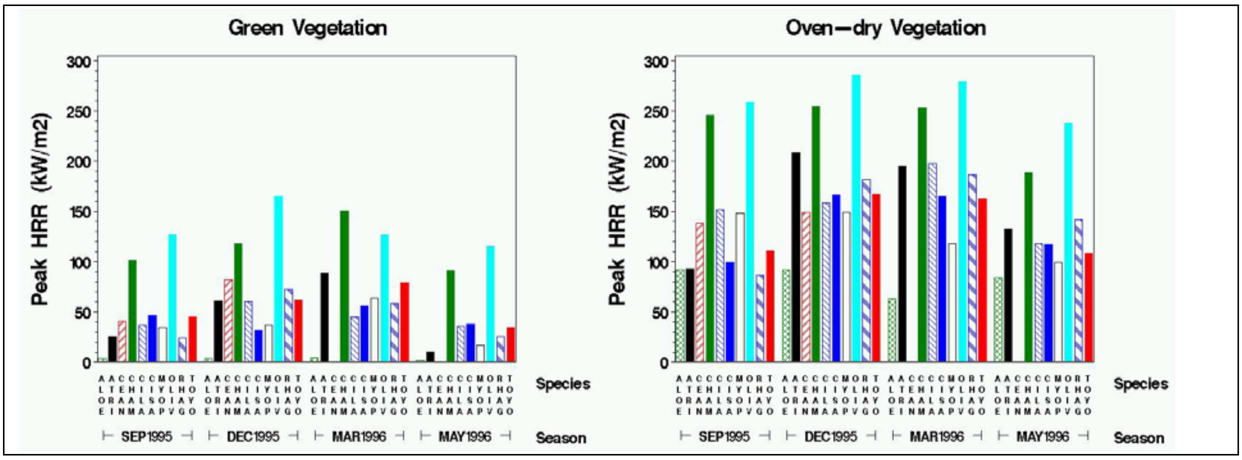

Figure 4. Mean peak heat release rates (HRR) for green and over-dry samples of ornamental vegetation in southern California. Peak HRR determined using 25 $kW\ m^{-2}$ flux in a cone calorimeter.

Table 2. Estimated peak heat release rates and effective heat of combustion for green and oven-dry samples of ornamental vegetation in southern California collected in between 8/1995 and 5/1996.

Species	O/G	Peak Heat Release Rate ($kW\ m^{-2}$)				Effective Heat of Combustion ($MJ\ kg^{-1}$)			
		AUG	DEC	MAR	MAY	AUG	DEC	MAR	MAY
Olea europaea	O	258	285	279	238	21.6	21.4	20.7	20.5
	G	127	165	126	115	9.9	10.5	9.3	8.7
Adenostoma fasciculatum	O	246	254	253	189	20.6	22.3	19.5	18.2
	G	102	118	150	91	8.6	10.6	10.4	8.3
Atriplex halimus	O	93	208	195	132	15.8	18.2	16.4	15.0
	G	26	61	89	11	1.7	5.1	4.2	1.6
Heteromeles arbutifolia	O	111	167	163	108	19.2	21.8	17.7	15.9
	G	45	62	79	34	4.2	7.0	5.5	3.0
Cistus ladanifer	O	152	159	197	118	18.2	19.5	18.4	14.9
	G	37	60	45	36	6.0	6.1	4.4	3.5
Myoporum parvifolia	O	148	149	118	99	20.2	20.0	17.0	16.2
	G	35	37	64	17	2.0	1.2	1.7	0.9
Ceanothus "Joyce Coulter" *	O	138	149			16.7	17.6		
	G	41	82			3.6	10.6		
Cistus salvifolius	O	99	166	164	118	15.8	17.7	15.6	13.7
	G	47	32	56	38	5.9	3.5	4.5	3.2
Aloe sp.	O	92	92	63	84	14.5	13.9	9.3	11.4
	G	4	4	4	1	-0.5	-0.4	0.2	0.2
Rhagodia spinescens	O	87	181	187	142	16.6	18.3	17.0	16.0
	G	24	73	59	25	2.9	5.9	2.8	1.8

* Ceanothus plant used for sampling died between 12/1995 and 3/1996.

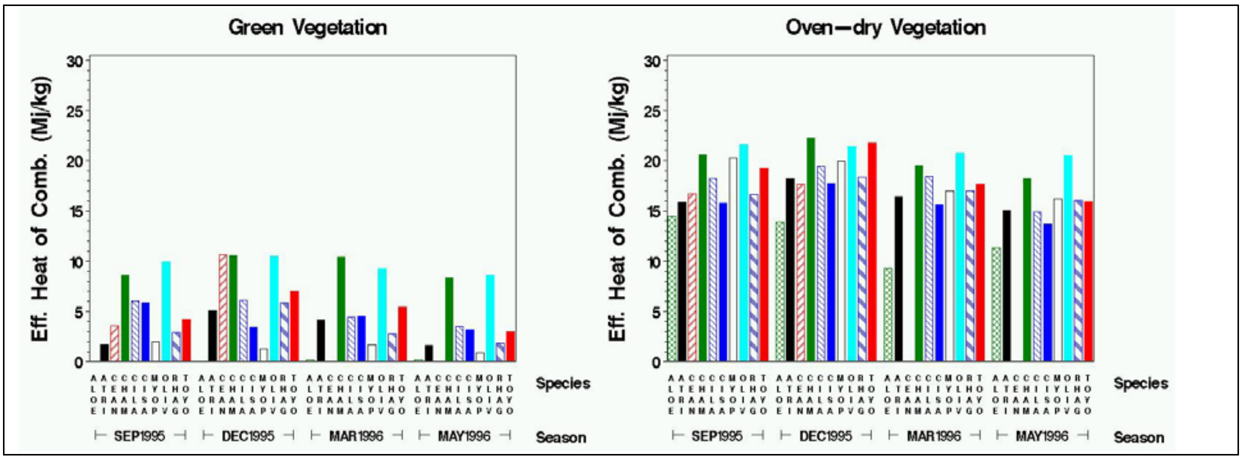

Figure 5. Mean effective heat of combustion (HOC) for green and over-dry samples of ornamental vegetation in southern California. HOC determined using 25 $kW\ m^{-2}$ flux in a cone calorimeter.

Table 3. Rank of cone calorimeter-based mean peak heat release rate for ornamental vegetation by season and fuel moisture content.

	August 1995		Dec 1995		Mar 1996		May 1996	
Species	Oven-dry	Green	Oven-dry	Green	Oven-dry	Green	Oven-dry	Green
Aloe	9.0	10.0	10.0	10.0	9.0*	9.0	9.0	9.0
Atri	8.0	8.0	3.0	5.0	4.0	3.0	3.0	8.0
Cean	4.0	5.0	8.0	3.0				
Cham	2.0	2.0	2.0	2.0	2.0	1.0	2.0	2.0
Cila	3.0	5.0	7.0	6.0	3.0	8.0	6.0	4.0
Cisa	7.0	3.0	5.0	9.0	6.0	7.0	5.0	3.0
Myop	4.0	7.0	9.0	8.0	8.0	5.0	8.0	7.0
Oliv	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
Rhag	10.0	9.0	4.0	4.0	5.0	6.0	4.0	6.0

*March and May 1996 only have ranks 1-9 since Ceanothus died between December 1995 and March 1996.

3.2 *Intermediate Scale Calorimeter Tests*

Thirteen tests were run in February 1996: 3 each for *Atriplex lentiformis, Rhagodia spinescens*, and *Cistus salviifolius*, and 2 each for *Ceanothus impressus* and *Rosmarinus officinalis.* A group of 4 plants was used for each *Atriplex, Cistus*, and *Ceanothus* test; 2 plants were used for *Rosmarinus* and 1 plant per test for *Rhagodia* (Fig. 6). The fine fuels (diameter < 6 *mm*) comprised a large percentage (60-80%) of the total mass of the samples (Table 4). Foliage moisture content ranged from 180 to over 300 %. Total sample moisture content was < ½ of the foliage moisture content for 4 of 5 species.

Figure 6. Arrangement of plants used in Intermediate Scale Biomass Calorimeter tests.

The range of measured leaf σ was 55 to 107 cm^{-1} and was much larger than σ for a 6 mm diameter cylinder (σ = 6.3 cm^{-1}). This indicated that the foliage fell within the 1-hr time-lag fuel class. The fuel packing ratios were similar between species and generally low when compared with litter fuel beds (0.056-0.064, Rothermel and Anderson 1966) and native chaparral stands (0.01-0.02, Weise et al. 2003). The percentage of volatile compounds contained in the foliage was essentially constant for 4 of the 5 species tested. *Rosmarinus* had a significantly higher percentage of volatiles by mass. Most of these volatiles were produced at temperatures < 300 °C. PHRR ranged from a low of 52 $kW\ m^{-2}$ for an *Atriplex* sample to >300 $kW\ m^{-2}$ for a *Rhagodia* sample. Average AHOC ranged from 5.8 $MJ\ kg^{-1}$ for *Rhagodia* to 21.6 $MJ\ kg^{-1}$ for *Cistus salviifolius*. AHOC for most samples was <10 $MJ\ kg^{-1}$.

3.3 *Comparison of Cone and ISBC Calorimeters*

A plot of PHRR did not suggest a strong relationship between the results from the cone and ISBC calorimeters (Fig. 7). There was no evidence of any trend in AHOC from the two calorimeters either.

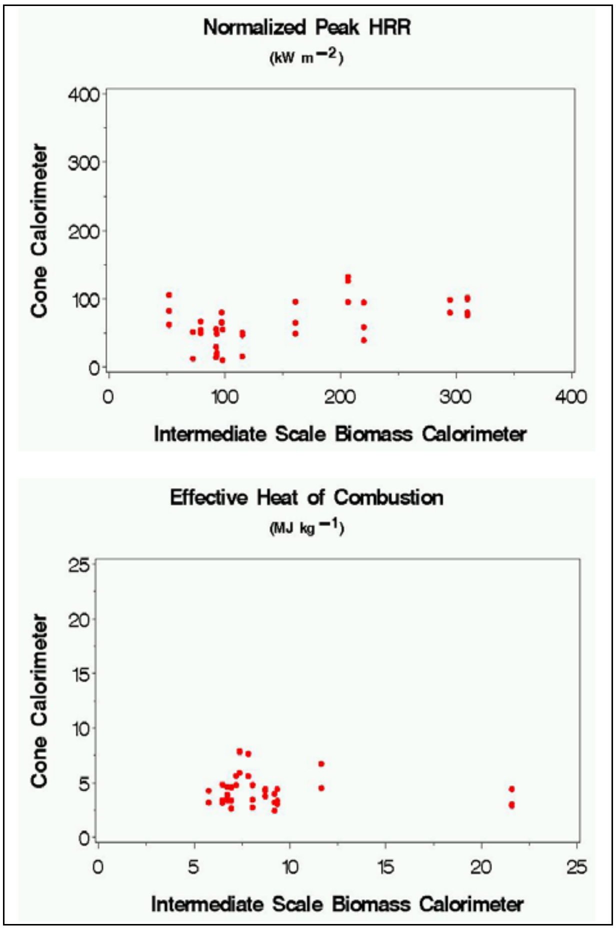

Figure 7. Relationship between PHRR and AHOC measured by a Cone Calorimeter and an Intermediate Scale Biomass Calorimeter.

Estimated correlations between the cone and ISBC calorimeter were *r=0.51* and *r=-0.15* for PHRR and AHOC, respectively. The PHRR correlation was significant; the AHOC correlation was not significantly different from 0.

4. DISCUSSION AND SUMMARY

Peak heat release rate measured by the cone calorimeter differed between species and season. Moisture content reduced PHRR appreciably but did not affect the ranking of the extremes. Estimated heat of combustion was also influenced by species and month of sampling; however, the influence of sampling month was not consistent. Because the plants that we used were living and actively maintaining the water content of foliage and branches through normal plant metabolism, the effects of sample moisture content and season are confounded. It is not possible in this study to definitively state that the observed differences in PHRR and AHOC between sampling times are solely caused by moisture content or by phenological or physiological differences in the plants as a result of the annual growth cycle.

Rhagodia spinescens, an Australian plant, had relatively high peak heat release rates at both the small and intermediate scales. *Atriplex* consistently had low PHRRs at both scales. *Ceanothus* and

Cistus PHRR values fell between the extremes at both scales.

While there was some agreement in relative flammability as measured by PHRR between the 2 calorimeters, the correlation between actual values of PHRR and AHOC was poor. Drysdale (1985) reported that heat of combustion for pure cellulose determined in an oxygen bomb calorimeter has been established as approximately 16 $MJ\ kg^{-1}$; average Gross heat of combustion for *Fagus sylvatica* (European beech) wood, a combination of cellulose, hemicellulose, and lignin, was higher (19.5 $MJ\ kg^{-1}$). All results for AHOC for the oven-dry samples fell between the results for cellulose and wood. This is to be expected since the samples were composed of foliage (primarily cellulose) and branches (wood). Dimitrakopoulos (2001) reported heat content of *Cistus salviifolius* between 18.65 and 19.05 $MJ\ kg^{-1}$.

While the cone calorimeter provided results that might be used to determine the flammability of a particular species, the applicability of this type of result to complete plants is currently unknown. The flammability of complete plants is influenced by the geometry of the plant in addition to other characteristics. More testing of paired samples of vegetation with the cone calorimeter and intermediate scale calorimeters is recommended before the cone calorimeter or other similar small-scale testing setup bee used to rate plant flammability.

Table 4. Physical characteristics of plant species used in Intermediate Scale Biomass Calorimeter tests.

Species	Fine fuel mass* (kg)	Moisture Content** (%)	Fuel Bed Height (m)	Leaf σ (cm^{-1})	Packing Ratio	Foliage Volatiles*** (%)	Particle Density ($kg\ m^{-3}$)
Atriplex lentiformis	0.33 (59)	291 (128)	0.60	57.8	0.005, 0.01	0.4	571
Ceanothus impressus	0.20 (77)	180 (142)	0.64	76.1	0.003	0.3	452
Cistus salvifolius	0.37 (64)	289 (107)	0.60	55.3	0.008	0.5	611
Rhagodia spinescens	0.78 (80)	304 (118)	0.41	61.9	0.006	0.4	622
Rosmarinus officinalis	0.54 (74)	201 (115)	0.43	106.8	0.008	3.8	608

*Oven-dry mass of material < 6 mm diameter. (Fine fuel dry mass/total dry mass (%)).
**Numbers are foliage (total) moisture content.
*** Volatile mass expressed as % of total oven-dry mass.

Table 5. PHRR and AHOC estimated by an Intermediate Scale Biomass Calorimeter for 5 species of ornamental plants in southern California.

Species	Normalized Peak HRR ($kW\ m^{-2}$)	Heat of combustion ($MJ\ kg^{-1}$)
ATRI	97.6	9.3
	79.4	9.2
	52.1	8.7
CEAN	72.8	7.2
	98.3	11.7
CISA	92.7	6.9
	93.4	8.0
	115.4	21.6
RHAG	309.9	6.7
	161.2	5.8
	220.4	6.5
ROOF	206.7	7.4
	294.8	7.8

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