CSIRO PUBLISHING

International Journal of Wildland Fire, 2007, **16**, 426–443 www.publish.csiro.au/journals/ijwf

Combustion characteristics of north-eastern USA vegetation tested in the cone calorimeter: invasive versus non-invasive plants

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Abstract. In the north-eastern United States, invasive plants alter forest fuels, but their combustion characteristics are largely unknown. We assessed unground samples of foliage and twigs in the cone calorimeter for 21 non-invasive, native species, paired with 21 invasive species (18 non-native). Variables included sustained ignition, peak heat release rate, total heat release, and especially average effective heat of combustion, which is independent of initial sample mass. Heat of combustion was overall slightly lower for invasive species than for counterpart non-invasive species, and was significantly lower for Norway maple, black locust, and glossy buckthorn than for three non-invasive trees. It was low for invasive Japanese stiltgrass, sheep sorrel, and glossy buckthorn, and for non-invasive whitegrass, interrupted fern, grape, sphagnum moss, and three-lobed bazzania. Heat of combustion was high for invasive roundleaf greenbrier (native), scotchbroom, tree-of-heaven, Japanese honeysuckle, Japanese barberry, swallow-wort, and garlic mustard, and for non-invasive plants of fire-prone ecosystems: black huckleberry, pitch pine, bear oak, northern bayberry, and reindeer lichen. Heat content of twigs and foliage interrelates with other factors that affect fire behaviour, yet the cone calorimeter results enabled comparison of combustion properties among many species. These data have potential application as improved inputs for fire behaviour modelling.

Additional keywords: fire, flammability, fuel, heat content, native, non-native, plants.

Introduction

Invasive plants such as Japanese barberry[1], oriental bittersweet and multiflora rose have become widely entrenched in forests and disturbed habitats of the north-eastern USA (Richburg *et al.* 2001; Dibble 2004; Dibble and Rees 2005). Problems that accompany invasive plants have been detailed for many types of ecosystems (e.g. McKnight 1993; Luken and Thieret 1997), and include displacement of native plant communities, impact on biodiversity, degradation of wildlife habitat, and changes in physical aspects of soils.

Dibble and Rees (2005) recently characterised fuels in four forest types – hardwoods, mixed woods, softwoods, and pitch pine – in 13 forested sites at 12 areas in the north-eastern USA. They compared invaded to uninvaded conditions within each site, and found no single pattern that held for all forest types, except that live fuels in the shrub layer were generally more abundant in invaded conditions. Where density of invasive plants was high, fuel characteristics differed substantially from that of the uninvaded plant community, especially in percentage cover, height and frequency of the shrub layer, but also in fuel depth and duff depth. Nearby uninvaded stands tended to have sparse shrub cover that was lower in height, with lower fuel depth and greater duff depth. In some forest stands, invasive grasses such as wood blue-grass (*Poa nemoralis* L.), Japanese stiltgrass (included in the present study), fine-leaved sheep fescue (*Festuca filiformis* Pourret), and sweet vernal grass (*Anthoxanthum odoratum* L.) changed the fuel bed by significantly increasing the load of continuous fine fuels. Japanese honeysuckle, Oriental bittersweet and other vines appear to add to the ladder fuels. These changes in fuels could either increase or decrease the fire return interval and fire intensity compared with fuels in the plant communities that become displaced. The influence of invasive plants might vary according to the heat content in each species, which is mostly unknown.

Wooded areas contain numerous homes in the wildland–urban interface of the north-eastern USA, and the fuels in these forests appear to be increasing. The fuels have been changing with reversion of agricultural fields to forest, with disturbance events such as an ice storm in 1998 that led to much breakage in hardwood forests, and with tree mortality due to pest and disease outbreaks (chestnut blight, gypsy moth, Emerald ash borer, hemlock woolly adelgid, balsam woolly adelgid, spruce bark beetle, and others). If invasive plants encroach in the disturbed canopy, then the load of live fuels can significantly increase when some

[1] See Table 1 for scientific names of species sampled in the present study.

 10.1071/WF05103 1049-8001/07/040426

invasive plants take over, especially near administrative holdings, residences, and farms where a seed source is likely. For example, in hardwood and mixed-wood stands in the eastern USA, non-native Japanese barberry, a shade-tolerant shrub, forms a dense layer of live fuels in the understorey, whereas nearby uninvaded conditions have only a sparse shrub layer. Not all invasive plants require forest openings, and some such as Japanese barberry and Japanese stiltgrass are capable of colonising even in mature forests (Dibble and Rees 2005).

In recent years, the region has been spared the enormous fire problems that have plagued the western USA with its extended droughts. But there is a history of large wildfires in this region, such as fires in Maine, USA, in October 1947 (Dibble *et al.* 2004). Only a few fuel datasets have been prepared in this region, including: (1) research by William A. Patterson III (University of Massachusetts, Amherst, Massachusetts, USA) and his students on Cape Cod and in other fire-adapted systems, and two ongoing projects funded by the National Fire Plan; (2) one led by Daniel Yaussy, 'Fuels and fire behaviour in the Central Hardwoods'; and (3) another by John Hom in the New Jersey pine barrens (both: US Forest Service, Northern Research Station, Newtown Square, Pennsylvania).

Fire managers need information about combustion characteristics as they develop custom fuel models to predict spread and intensity of fires based on the species present. Recent development of the Fuel Characteristic Classification System (FCC; Ottmar *et al.* 2003) has been a major improvement in uncovering aspects of fuels but its relevance to fuelbeds in north-eastern North America is untested, to our knowledge. Models may be unreliable if based on anecdotal observations, intuition, and data collected from species native to other parts of the continent. Prescribed fire in this region is typically intended to maintain a desired plant community, or for hazard fuel reduction or to control invasive plant populations. Managers are more likely to achieve their goals if they have information about combustion characteristics that is specific to the plant species they encounter on the landscape, rather than information based on extrapolations from other plant species and vegetation types. Such data could be important for maintaining a fire-adapted ecosystem such as pitch pine–scrub oak, a cover type that is vulnerable to conversion by a virtually non-flammable tree, black locust. Fire-adapted species such as the blue lupine (*Lupinus perennis* L.), host plant for the federally endangered Karner blue butterfly (*Lycaeides melissa samuelis* Nabakov), would be lost if fire is suppressed in the pitch pine–scrub oak type.

Information about heat content for many commercially important hardwoods and conifers is available as 'heating value' based on data collected in the oxygen bomb calorimeter. Recently, tests were conducted on species from hardwood hammock and pine flatwoods of the southern USA (Behm *et al.* 2004). Most such USA research has been on species of the fire-prone ecosystems of the south-west (Weise and Saveland 1996; White *et al.* 1996, 2002; Weise *et al.* 1998, 2005; Etlinger and Beall 2004). For most plants including native and non-native shrubs, vines, herbs, and for lichens and bryophytes, there are few data on flammability. Besides our own preliminary reports (White *et al.* 2002; Dibble *et al.* 2003), there has not been a comparison of combustion characteristics in invasive plant species with those of common species they might be displacing in many wildland–urban interface fuel beds.

In the present study, we used a fire test apparatus known as the cone calorimeter to test samples of foliage and twigs. The cone calorimeter is widely used to evaluate the combustion characteristics of building materials and uses a cone heater to expose the test material placed in a 100 by 100 mm sample holder to a constant heat flux. The primary results are the heat release rate curve, which is obtained by measuring the consumption of oxygen due to combustion, and the mass loss rate curve. The average effective heat of combustion (AEHOC), in MJ kg^{-1}, is calculated from the heat release and mass loss data for the duration of the test.

Our objective was to test the hypothesis that there is no difference between the AEHOC of foliage and twigs in non-invasive *v.* invasive plants that are common in the wildland–urban interface in the north-eastern USA.

Background

This section provides background information on flammability of vegetation, the evaluation of combustion characteristics, and the application of the cone calorimeter to vegetation. Additional information can be found in Etlinger and Beall (2004) and Weise *et al.* (2005).

Combustion is not a single process, but has multiple interrelated components, some of which have not been measured much yet. Martin *et al.* (1994) thought that the flammability of vegetation and vegetative material had not been well defined or measured to any great extent. Flammability is affected by many factors such as heat content, moisture content, chemical composition, arrangement of fuels in three dimensions (as in needles, leaves, fine twigs, or loose bark), surface area-to-volume ratio (SAV), fuel bed porosity, and fuel depth. Variability within these parameters has not been clearly elucidated, nor is it reported in the Photo Series (overview available online, http://depts.washington.edu/nwfire/factsheet/factsheet_ps.pdf; verified 24 October 2006). There is no standardised protocol for measuring vegetation flammability or combustion characteristics (Stephens *et al.* 1994; Behm *et al.* 2004; Etlinger and Beall 2004). One common approach is to replace the direct measurement of fire performance with measurements of physical and chemical properties or characteristics of the vegetation and the amount of biomass. Use of physical and chemical properties or characteristics of the vegetation in combination with the amount of biomass was also used by Behm *et al.* (2004) in their investigation of native understorey species in pine flatwood and hardwood hammock ecosystems.

In the Rothermel (1972) model, the only combustion property included is the heat content or heat of combustion. The fuel particle heat content is that measured using an oxygen bomb calorimeter, which combusts the material completely (or nearly so) and measures the heat given off in the process. Input for early versions of the BEHAVE fire behaviour prediction model is specified as oxygen bomb calorimeter data from vegetation samples that have been ground. Burgan and Rothermel (1984) noted that higher heat content produces more intensive fire behaviour, and thought the relationship was direct and predictable. Other parameters used in the model include SAV ratio, fuel bed porosity, fuel depth, fuel loading, fuel particle moisture content, and fuel particle mineral content. Sensitivity analyses revealed that the first three of these are the most important variables in the Rothermel model (D. Weise, pers. comm.). An updated version of BehavePlus puts more emphasis on fuel moisture than on heat content in modelling (Andrews *et al*. 2005). Practitioners in the north-eastern region often select one of the 13 standard models in BEHAVE, employ constants and inputs that were derived in western USA fuel beds, run the model, collect fire behaviour data (e.g. flame length, rate of spread) and then modify the model. They might base their model selection on attributes that are not pertinent to the species they see on the landscape, and they do not have access to heat content data for many species in the fuel beds they are modelling, especially in the shrub and herb layers. Whereas they can select within a range of 13 967–27 934 kJ kg^{-1} (6000–12 000 BTU lb^{-1}; Andrews *et al*. 2005), the reliability of the predictions could be compromised by uncertainty surrounding parameters such as heat content.

Those who study fuels have not reached a firm consensus regarding terminology. They typically reference the three components of vegetation flammability identified by Anderson (1970): ignitability, sustainability, and combustibility. Martin *et al*. (1994) expanded this list to include a fourth component: consumability. The only component associated with test methodologies was ignitability, which was measured as the ignition delay, i.e. the time for ignition. Not only are the components somewhat dependent on each other, but ignitability is a factor in the other three components. Combustibility was described as how rapidly the fuel burns, sustainability as how well the fuel continues to burn, and consumability as how much of the fuel burns. Martin *et al*. (1994) noted that all four flammability characteristics depend on volatile extractives, size, density, moisture content, continuity, compactness and quantity.

For a sample of foliage or twigs, the cone calorimeter test can be used to obtain combustion characteristics that provide a measure of some of the components of combustion identified by Anderson (1970) and Martin *et al*. (1994). Continuation or sustainability of a fire depends on the ignition characteristics of the fuel and the heat evolved in the combustion of the fuel, which is AEHOC or total heat released (THR). The ignitability of the sample is obtained by recording the time for sustained ignition (TSI) of the test sample. The peak or maximum heat release rate (PHRR) is an indicator of the rapidity of the combustion of the fuel (i.e. combustibility). Recording the residual mass fraction (RMF) of the sample provides information on how much of the fuel is consumed (i.e. consumability) under the specified test conditions. There is not yet a suitable model for combining different test results from the cone calorimeter into a single measure of relative flammability of vegetation.

Other applications where the cone calorimeter was used to evaluate relative combustion properties of plant material include a study of western vegetation (White *et al*. 1996; Weise *et al*. 2005), and those data were compared to a subset of the data reported here (White *et al*. 2002). Enninful and Torvi (2005) studied conifer fuels and investigated the effect of moisture and incident heat flux on smoke production and heat release rates obtained in a cone calorimeter. Blank *et al*. (2006) used a cone calorimeter to investigate the combustion properties of *Bromus tectorum* L.

When evaluating AEHOC results from the cone calorimeter as a substitute for the heat content from the oxygen bomb calorimeter, the completeness of consumption in the natural fires or the fire model assumptions need to be considered. In the oxygen bomb calorimeter, there is no residual char, the influence of higher lignin content is to increase the heat content, and the net heat content (or heat of combustion) of wood would be 16–18 kJ g^{-1} (Janssens 2002). White (1987) reported a significant correlation between the higher heat content of different wood samples in the oxygen bomb calorimeter and the Klason lignin content for extractive-free wood and concluded that the correlation reflected the higher heat content of lignin relative to cellulose and hemicellulose. In contrast, as much as 20–30% of a wood sample can remain unconsumed in the cone calorimeter and the AEHOC would be 12–13 kJ g^{-1} (Janssens 2002). The THR per unit mass depends on the amount of the sample that is consumed by combustion. Lignin on pyrolysis yields more residual char than is obtained from cellulose (Browne 1958). Thus the AEHOC reflects the heat content due to combustion of the extractives, cellulose, and hemicellulose contents of the vegetation. The cone calorimeter is designed so there is sufficient oxygen for complete combustion of the pyrolysis products. The only product of incomplete combustion accounted for in the test is carbon monoxide. Any other incomplete combustion of the pyrolysis products in a cone calorimeter test (such as before ignition of the combustible gases by the spark igniter) will result in lower values of the AEHOC. A potential future study is one that includes comparative cone calorimeter and oxygen bomb calorimeter data and tests to identify phytochemicals (Susott *et al*. 1995) that drive those differences.

The confinement of the cone calorimeter sample holder and the expression of some results in terms of exposed surface area require that judgment be used in the selection of materials to include in the small holder. The actual surface area of the vegetation exposed to the incident heat flux likely affects the test results. When a bed of test materials is placed in the holder, factors that need to be considered are the percentage of the sample holder that is covered by vegetation, the total mass of the sample, and the gross thickness of the layer of test material. In studies of White *et al*. (2002), the main criterion was to place sufficient unground material to cover as much of the sample holder as practical without resulting in a thick bed of materials. In their tests of jack pine and balsam fir needles and small branches or twigs, Enninful and Torvi (2005) packed the materials into the sample holder so as to maintain a consistent bulk density from specimen to specimen. One alternative to using the actual leaves, needles and twigs would be to use ground materials, as is done for oxygen bomb calorimeter or thermal analysis equipment. The ground material would uniformly cover the exposed surface of the sample holder. This approach was taken by Blank *et al*. (2006) in the study of the combustion properties of *Bromus tectorum* L., who found that repeatability of results was improved if the total mass of the samples was kept as a constant. The main disadvantage of using ground samples is the loss of the effect of the plant material structure on its relative combustibility.

The oxygen consumption calorimeter methodology of the cone calorimeter has also been used to test full size plants (Stephens *et al*. 1994; Etlinger and Beall 2004; Weise *et al*. 2005). Although providing a more realistic sample and important information, such testing introduces the increased variability of the structure of the plant. Each scale of testing – small ground samples, small branches with foliage, and full-size plants – has its own strengths and limitations. Only a few direct comparisons have been conducted using both full-scale testing and cone calorimeter testing (White *et al*. 1997; Weise *et al*. 2005). It is clear that overall physical characteristics of an entire plant are more important than individual combustion properties in the flammability of vegetation (Behm *et al*. 2004; Etlinger and Beall 2004).

Materials and methods

Sampling

We selected non-invasive species (Table 1) based especially on their potential to occupy a large proportion of the fuel load within their forest stratum. All non-invasive species are native to the region (Fernald 1950). We called a species 'invasive' if it (1) is generally targeted for treatment in fuel beds (e.g. native roundleaf greenbrier, black locust, and non-native scotchbroom); (2) has become invasive outside of its native range (e.g. eastern ninebark is invasive in Acadia National Park, Bar Harbor, Maine, but is native in the Appalachians north to eastern Pennsylvania); or (3) is widely recognised as a non-native pest plant in north-eastern North America (e.g. Japanese honeysuckle; see Mehrhoff *et al*. 2003 for other examples). The invasive species of Table 1 are common in the region and might displace dominant native species, though we can find no data by which to compare pre-invaded with post-invaded vegetation for a given site. Under some circumstances, bear oak (also known as shrub oak) is considered invasive where open habitats are desired (e.g. south coastal Massachusetts), but because it is a native component of the fire-adapted pitch pine type, we assigned it as 'non-invasive' for the present study.

We paired 21 invasive species each with a non-invasive species (Table 1) based on: (A) data from one or more sites studied by Dibble and Rees (2005) for documented co-occurrence of two species at the same sites and in the same habitats; or (B) arbitrary designation based on our casual observation of niche at multiple sites, especially regarding topography, drainage patterns, and response to disturbance, but not necessarily based on known, documented co-occurrence. Some species are directly displaced by another, e.g. 'non-flammable' black locust shades out the vegetation in pitch pine–bear oak stands at the Albany Pine Bush Preserve, Albany, New York. Unless prescribed fire is applied, an infestation of black locust leads to loss of the dominant trees and fire-adapted understorey plants (Dibble and Rees 2005). For species pairs in category B, direct displacement has not been quantified (e.g. we know of no data to detect that white-grass was displaced by garlic mustard), but we suggest there is potential for the two to co-occur and for the invasive species to outcompete the non-invasive species. In another example for category B, we observed that sheep sorrel is invasive in reindeer lichen–bryophyte habitats over thin soil or exposed bedrock in the region. There are eleven species pairs in category A, for which we have documentation, and ten pairs in category B.

During the course of the present study, we conducted three series of tests in the cone calorimeter (2001–2003). The samples for these tests were obtained from nine sites in the eastern and mid-Atlantic USA (Maine, Maryland, Massachusetts, New York, and Virginia). We obtained leaves and twigs of 38 species of vascular plants, three bryophytes, and one lichen (Table 1). Fresh, live material was collected into paper bags from plants in full leaf, and did not include roots, cones, flowers or fruits. Samples were dried to constant weight in a vegetation drying room (60°C) at the University of Maine at Orono, Maine, then shipped to the Forest Products Laboratory (FPL) in Madison, Wisconsin for testing. Samples were stored in a 27°C, 30% relative humidity room at FPL before testing. As a result, the moisture content of the samples was ~7.5% of the oven-dry mass. This conditioning protocol was selected because full oven-drying of the samples at 103°C can result in the loss of volatiles before the fire test. The disadvantage of not oven-drying the samples is that the loss of mass due to loss of moisture is included in the AEHOC calculations. Assuming all moisture is driven off in the test, the AEHOC on an oven-dried basis is ~8.5% less than that reported in the present paper. Testing of green samples involves greater uncertainty in the mass loss of the dry vegetative matter and test results that are greatly influenced by variations in moisture content (Weise *et al*. 2005).

Cone calorimeter

The vegetation samples were tested in an oxygen consumption calorimeter known as the cone calorimeter (Babrauskas 1984, 2002). The methodology standards are ISO 5660-Part 1 (International Organization for Standardization 2002) and ASTM E1354 (ASTM International 2002). The ASTM standard methodology for the operation of the cone calorimeter was followed. The cone calorimeter at FPL was a Model CONE2 AutoCal, manufactured by Atlas Electric Devices Company of Chicago, IL.

The unground pieces of the fine fuels were placed in a sample holder that included the optional retainer frame and grid (Weise *et al*. 2005). For Series I, we used three replicates per species. Coverage of the surface area of the sample holder was the primary basis for the amount of sample used in this first series of runs. For Series II, we added two additional replicates of the initial group of species in which the initial sample mass and the thickness of the layer of test material was approximately doubled. This was done to obtain data on the effect of the initial sample mass on the test results. In Series III, which was a group of samples of additional species, the initial sample mass was similar to that of Series I, and this time six replicates were used.

The electric cone heater was set to expose the horizontal specimen in air to a constant heat flux of 25 kW m^{-2}. This low heat flux was selected to increase the likely sensitivity of the test results to differences between the dry samples of the various species. One disadvantage of a low heat flux level is an increased likelihood that some mass loss occurs before sufficient flaming for complete combustion of the pyrolysis products. The only product of incomplete combustion that is accounted for is carbon monoxide. Plants in natural fires are likely to be subjected to a wide range of heat flux levels. The cone calorimeter is capable of exposing the specimen to a constant heat flux up to 100 kW m^{-2}. A spark igniter was used to provide the piloted ignition. Gas analysers measured the oxygen, carbon monoxide, and carbon dioxide in the exhaust stack. A 41-mm orifice plate was used for a measured exhaust flow of 0.012 m^3 s^{-1}. The scan rate for the measurements was 1 scan per second.

Table 1. Plants sampled for the present study

Species and common name, status as native and invasive, pairing for comparison of heat content, support for decision of pairing, code and growth habit. Information based on the database maintained by the US Department of Agriculture (USDA, Natural Resources Conservation Services 2004). Pairs based on 'A', data regarding co-occurrence from one or more sites reported in Dibble and Rees (2005); or 'B', proposal based on casual observations of niche including soil moisture, pH, and response to disturbance from various sites in the north-eastern USA, not on actual data

Species names	Common name[A]	Native to North America[B]	Considered invasive	Pair no.	Reference or other source	Code	Growth habit
Acer rubrum L.	red maple	yes	no	1	A	ACRU	tree
Acer platanoides L.	Norway maple	no	yes			ACPL	tree
Populus tremuloides Michx.	quaking aspen	yes	no	2	A	POTR5	tree
Ailanthus altissima (P. Mill) Swingle	tree-of-heaven	no	yes			AIAL	tree
Prunus virginiana L.	chokecherry	yes	no	3	A	PRVI	tree, shrub
Malus sylvestris P. Mill	European crabapple	no	yes			MASY2	tree, shrub
Pinus rigida P. Mill	pitch pine	yes	no	4	A	PIRI	tree
Robinia pseudoacacia L.	black locust	yes	yes			ROPS	tree
Quercus ilicifolia Wangenh.	bear oak	yes	no[C]	5	B	QUIL	tree, shrub
Elaeagnus angustifolia L.	Russian olive	no	yes			ELAN	tree, shrub
Amelanchier canadensis (L.) Medik	Canadian serviceberry	yes	no	6	A	AMCA4	tree, shrub
Physocarpus opulifolius (L.) Maxim	common ninebark	yes[D]	yes			PHOP	shrub
Alnus incana (L.) Moench ssp. *rugosa* (Du Roi) Clausen	speckled alder	yes	no	7	A	ALINR	tree, shrub
Frangula alnus P. Mill.	glossy buckthorn	no	yes			FRAL4	tree, shrub
Viburnum dentatum L.	southern arrowwood	yes	no	8	A	VIDE	tree, shrub
Berberis thunbergii DC.	Japanese barberry	no	yes			BETH	shrub
Viburnum acerifolium L.	mapleleaf viburnum	yes	no	9	B	VIAC	shrub
Berberis vulgaris L.	common barberry	no	yes			BEVU	shrub
Gaylussacia baccata (Wangenh.) K. Koch	black huckleberry	yes	no	10	B	GABA	shrub
Lonicera japonica Thunb.	Japanese honeysuckle	no	yes			LOJA	vine
Vaccinium corymbosum L.	highbush blueberry	yes	no	11	B	VACO	shrub
Cynanchum cf. *louiseae* Kartesz & Gandhi	Louis' swallow-wort	no	yes			CYLOP11	vine, forb/herb, perennial
Morella pensylvanica (Mirbel) Kartesz, comb. nov. ined. (syn. *Myrica pennsylvanica*)	northern bayberry	yes	no	12	B	MOPE6	tree, shrub
Cytisus scoparius (L.) Link	scotchbroom	no	yes			CYSC4	shrub
Vitis sp.	grape	yes	no	13	A	VITIS	vine
Celastrus orbiculatus Thunb.	oriental bittersweet	no	yes			CEOR7	vine
Rosa carolina L.	pasture rose	yes	no	14	B	ROCA4	subshrub, shrub
Rosa multiflora Thunb. ex Murr.	multiflora rose	no	yes			ROMU	shrub, vine
Solidago rugosa P. Mill.	wrinkleleaf goldenrod	yes	no	15	A	SORU2	forb/herb
Smilax rotundifolia L.	roundleaf greenbrier	yes	yes			SMRO	shrub, subshrub, vine
Leersia virginica Willd.	whitegrass	yes	no	16	A	LEVI2	graminoid
Polygonum cuspidatum Sieb. & Zucc.	Japanese knotweed	no	yes			POCU6	subshrub, shrub forb/herb
Osmunda claytoniana L.	interrupted fern	yes	no	17	A	OSCL2	forb/herb
Lythrum salicaria L.	purple loosestrife	no	yes			LYSA2	subshrub, forb/herb
Cladonia rangiferia (L.) Nyl.	reindeer lichen	yes	no	18	B	CLADO	non-vascular/lichen
Rumex acetosella L.	common sheep sorrel	no	yes			RUAC3	forb/herb
Sphagnum fallax (Klinggr.) Klinggr.	sphagnum moss	yes	no	19	B	SPHAG2	non-vascular/moss
Microstegium vimineum (Trin.) A. Camus	Japanese stiltgrass	no	yes			MIVI	graminoid, annual
Bazzania trilobata (L.) Gray	three-lobed bazzania	yes	no	20	B	BATR5	non-vascular/ liverwort
Solanum dulcamara L.	climbing nightshade	no	yes			SODU	subshrub, forb/herb
Pleurozium schreberi (Brid.) Mitt.	Schreber's big red stem moss	yes	no	21	B	PLSC70	non-vascular/moss
Alliaria petiolata (Bieb.) Cavara & Grande	garlic mustard	no	yes			ALPE4	forb/herb

[A] Exceptions: USDA Plants database uses 'Nepalese browntop' for Japanese stiltgrass and 'Carolina rose' for pasture rose.
[B] Status as native was based on Fernald (1950).
[C] Considered invasive in some areas where management priority is to maintain early-successional openings.
[D] Invasive plants that are native farther south in North America but introduced in the north-eastern region where sampled.

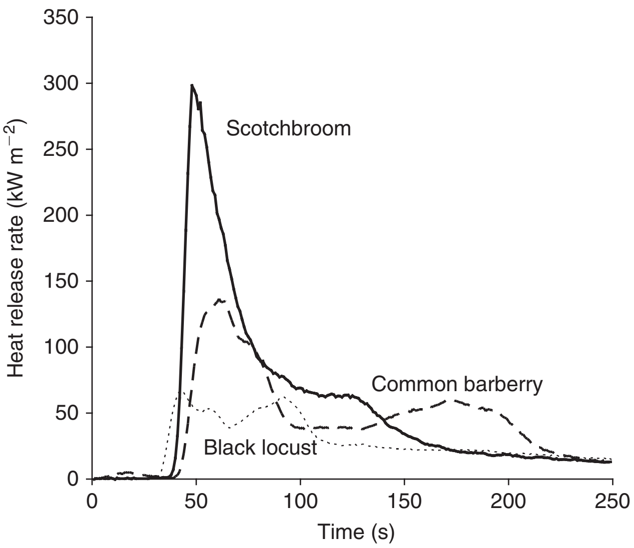

Fig. 1. Selected heat release rate curves for scotchbroom, black locust, and common barberry (Table 1). Initial sample masses of these three samples were between 6.59 and 6.83 g.

The initial sample mass (MASS0, g), was measured just before inserting the test specimen under the heater. A load cell under the specimen measured the mass loss. Final mass was measured for comparison. Using the measurement of oxygen, carbon monoxide and carbon dioxide and the flow rate of the exhaust gas, the heat release rate was calculated. The calculations are based on the relationship that the heat release is 13.1 MJ per kg of oxygen consumed (Janssens 2002). The primary result from the cone calorimeter is a curve of the heat release rate *v.* time (Fig. 1). Numerical results from this curve that are generally reported include the PHRR, the average heat release rate over various time intervals, and the THR. For results that are reported on a sample area basis, i.e. the PHRR ($kW\,m^{-2}$), the area of the opening of the retainer frame ($0.0080\,m^2$) was used in the calculations. THR is calculated as the summation of the heat released during the test. For the present study, we are reporting the THR on a 'per initial mass' basis ($MJ\,kg^{-1}$). AEHOC is the total heat release divided by the mass loss ($MJ\,kg^{-1}$). To clarify the distinction between the AEHOC and the THR, we also calculated the RMF, which was the final sample mass divided by the initial sample mass on a percentage basis. TSI (s) was the visually observed ignition of the test sample that resulted in sustained flames for 10 s.

Statistical analysis

Individual response variables (AEHOC, PHRR, THR and TSI) were analysed with a two-factor nested analysis of variance. The first factor was species and, because the overall design of the experiment involved three series with different thicknesses, the thickness of the layer of test material in the sample holder was considered a fixed, nested treatment factor (within species). Thickness was not random, nor did we consider thickness to be directly comparable across species, and we tested different species at multiple thicknesses. Models were fitted in SAS V8.2 (SAS Institute, Inc. 1999), with least-squares means calculated for each species. That is, the overall mean for a species tested at multiple thicknesses was estimated by the mean of the means at different thicknesses of a material as opposed to the mean of all the observations in a species across the three series of runs. Residual patterns were examined for non-normality; however, responses in the present report are not adjusted for this. Also, censoring occurred for TSI within several species in that the test was stopped before a response could be recorded. These are noted in the graphs, but were not included in the analysis; thus, values reported likely underestimate the true value in those particular cases, and our estimate of error could be underestimated as well.

AEHOC, PHRR, TSI and THR might have been affected by the moisture content, density, thickness or mass of the sample, or some combination, when placed in the sample holder before the actual cone test was conducted. The AEHOC values were not corrected for mass loss due to moisture loss. Density was not measured. Thickness was a nested, fixed factor in the statistical models, whereas initial mass was evaluated as a possible covariate in analysis of covariance models. With these types of models, variables not affected by the cone test itself can be used to adjust other responses, such as PHRR, and to evaluate those responses at a common value or set of common values for the covariate. A linear adjustment for initial mass was used only for the THR results.

Comparisons of species were evaluated by three groupings of the species. The first grouping was by species growth form (designated according to USDA, Natural Resources Conservation Services 2004), and categories included overall, trees, shrubs, vines, and herbs. Non-invasive, non-vascular species were categorised under herbs. Swallow-wort was grouped with the vines, though it might be considered a tender shrub (Table 1). The second grouping was based on the non-invasive/invasive species pairing discussed above (Table 1). Two different sets of pitch pine were tested and treated as separate materials as a way of assessing the repeatability of the data for a woody species. The third grouping was by forest type with broad designations: hardwoods, softwoods, mixed woods, and fire-adapted pitch pine. For this grouping, we compared AEHOC for non-invasive *v.* invasive species that had been documented along transects or associated with plots at study sites in Maine, New York and Vermont as part of the fuels characterisation study described above (Dibble and Rees 2005). Sites were selected for inclusion here if they had at least five species for which we obtained AEHOC data in this present study. All four sites had numerous other, mostly native, non-invasive species present but combustion data are lacking for these.

We compared results by growth form and species pairs using linear contrasts (single comparisons within the linear models) to obtain estimates and comparison-wise P-values. To control false positives in planned comparisons, we used a multiplicity adjustment for each response, which is a family-wise adjusted P-value such that the collection of comparisons for that response is held to the 0.05 level. This was done by the simulation method from Westfall *et al.* (1999). Groups were considered different with a significance level of 0.05.

We assumed that most materials would exhibit differences based on the thicknesses tested. For several species, we tested for such differences in responses within the species. Initial mass of the 24-mm thick specimens (Series II) was typically double that of the 12-mm thick specimens, with some exceptions. Thickness measurements were not precise.

Because of the complicated nature of the variables in the context of the experiment, relationships between initial sample mass (MASS0, g), sample thickness (Thick, mm), AEHOC (MJ kg^{-1}), PHRR (kW m^{-2}), TSI (s), THRMJ (MJ), and RMF were explored with principal component (PC) analysis. We based this on the sample correlation matrix of the species by thickness means because, although thickness is not directly comparable across species, combined with other variables it could help us further understand relationships between the variables. We assessed the ordination by examining vector length and projection in relation to the arrangement of observations in biplots in which each vector is a function of the component loadings for that variable. Length of vector indicates the relative contribution of a variable to the ordination. The angle between two vectors indicates the degree of correlation between two variables. A small acute angle between two vectors indicates positive correlation between those two variables, a right angle indicates lack of correlation, and vectors with straight angles are negatively correlated. Each point represents an observation (group mean) and is plotted from its relative principal component scores in the first two principal component dimensions (Gower and Hand 1996). For this PC analysis, the THR data included were the actual total heat release of the test sample (THRMJ) in MJ, rather than the THR per unit mass (MJ kg^{-1}) reported elsewhere in this present paper. Groups with censored TSI values were excluded.

Individual responses for AEHOC, PHRR, and TSI were graphed with Trellis Graphics in S-PLUS (Insightful Corporation 2001) by species and invasiveness, with the least-squares mean estimate marked for each species. Censored TSI results were not included.

Results

Across our various groupings of the samples of foliage and twigs, the invasive species had slightly to significantly lower AEHOC than did the non-invasive species, though invasive vines had higher AEHOC than non-invasive vines, and there were additional exceptions among some species pairs (elaborated below). We found no overall trend that grouped non-invasive or invasive plant species into discrete groups. Average values by species differed according to the variable we measured, e.g. black huckleberry had the highest values for THR and AEHOC but was fourth highest in PHRR and thirteenth fastest in TSI. Common sheep sorrel was consistent in having the lowest average for THR, AEHOC and PHRR. There was also no sustained ignition observed in the tests of common sheep sorrel.

Initial mass

We examined the effect of initial mass of a sample on TSI, PHRR, THR, and AEHOC. Because variations in the initial sample mass and gross thickness of the layer of the test material possibly affected some test results, the differences in the initial samples were carefully analysed and included in the tables of the test results (Table 2). The initial sample mass for the individual tests ranged from 2.0 to 25.4 g with an overall average of 7.8 g. In the cone calorimeter test, the quantity of the sample is defined in terms of the 100 by 100 mm-surface area of a planar sample in the sample holder. The amount of material placed in the sample holder (i.e. thickness of the layer or mass of test material) is an arbitrary variable of the test method. The initial mass of the samples for Series II were intentionally approximately double the masses used for that species in Series I. Initial sample mass was significantly different for 14 of the 21 species pairs (Table 2).

Principal component analysis

The first two principal components and loadings explained 75% (47% and 28% respectively) of the variation based on the correlation matrix. When the within-sample variation was included, the analysis resulted in a similar decomposition with reduced weights (69% total, 41% first PC, 27% second PC). In a biplot of the first two principal component axes, all vectors were long enough to be considered important to the ordination (Fig. 2); THRMJ and PHRR were longest, followed by MASS0 and AEHOC. TSI was shortest. The biplot indicated a high degree of correlation between the AEHOC and PHRR (Fig. 2). There were only weak associations between AEHOC and variables we measured other than PHRR. We found a lack of correlation with MASS0, THRMJ, TSI, thickness (Thick), or RMF, though these other variables were correlated with some extent with each other (Fig. 2). As one would expect, the plot indicated a high degree of correlation between the THRMJ and MASS0. Some correlation was indicated between the TSI and the MASS0. Note that, generally, for species that were tested at multiple thicknesses and initial masses, the segment joining those two tended to be approximately perpendicular to AEHOC and PHRR; e.g. 9I and 9N are each represented twice in Fig. 2; these are differing test thicknesses and sample masses for mapleleaf viburnum and common barberry. Their observations are arrayed in a horizontal line across the plot. Otherwise, the observations did not form clouds of points that are suggestive of any group such as invasive *v.* non-invasive, or trees *v.* herbs. This lack of clear trends is consistent with our preliminary analyses.

Average effective heat of combustion

The AEHOC values for the individual tests ranged from 6.3 to 18.6 MJ kg^{-1}, with an overall average of 13.4 MJ kg^{-1}. A graphic portrayal of the AEHOC data (Fig. 3) shows that non-invasive black huckleberry, of fire-adapted ecosystems, had the highest AEHOC, followed by the invasive scotchbroom and the two sets of non-invasive pitch pine (with results similar to each other). Other species with high values for AEHOC were northern bayberry, Japanese barberry, roundleaf greenbrier, and bear oak. Lowest values were found for common sheep sorrel, three-lobed bazzania, Japanese stiltgrass, oriental bittersweet, sphagnum moss, and black locust. Using all the tests as the dataset, an unweighted linear regression (zero-intercept) of the THRMJ (MJ) with the mass loss (kg) resulted in a slope of 14.2 MJ kg^{-1}.

Most species tested at multiple thickness groupings did not exhibit differences in AEHOC between the thicknesses, but oriental bittersweet, climbing nightshade, and speckled alder had highly significant differences (P-values <0.0001). Other species, including glossy buckthorn, interrupted fern, mapleleaf

Table 2. Mean initial sample mass of the cone calorimeter samples

Listed are species pair, species, number of replicates, mean for sample, percentage covariance, mean for species, and linear contrast test results for difference between non-invasive and invasive species. Significance values are the unadjusted comparison-wise error rate and, in parentheses, the simultaneous error rate (to avoid false positives when conducting numerous comparisons). Each invasive plant was paired with a non-invasive plant. The non-invasive plant is listed first. N, Number of samples tested

Pair no.	Species	N	Initial sample mass			Significance at 0.05
			Mean (g)	COV (%)	Mean (g)	
1	red maple	3	3.9	11	6.67	
		2	9.4	1		0.2356
	Norway maple	3	4.5	2	6.06	(0.9971)
		2	7.6	0.3		
2	quaking aspen	3	6.6	1	9.39	
		2	12.2	10		<0.0001
	tree-of-heaven	6	6.6	24	6.56	(<0.0001)
3	chokecherry	4	5.9	7	7.49	
		2	9.1	1		<0.0001
	European crabapple	3	12.8	2	19.05	(<0.0001)
		2	25.3	0.3		
4	pitch pine 1	6	10.0	2	10.02	
	pitch pine 2	6	10.8	3	10.77	<0.0001
	black locust	3	6.6	5	15.68	(<0.0001)
		2	24.8	3		
5	bear oak	6	6.2	6	6.21	<0.0001
	Russian olive	3	8.9	6	13.90	(<0.0001)
		2	18.9	0.5		
6	Canadian serviceberry	3	5.4	2	7.94	
		2	10.5	0.5		<0.0001
	common ninebark	3	7.4	1	10.90	(<0.0001)
		2	14.4	1		
7	speckled alder	3	5.0	5	8.82	
		2	12.7	1		<0.0001
	glossy buckthorn	3	3.2	6	4.91	(<0.0001)
		2	6.6	6		
8	southern arrowwood	3	9.7	11	14.84	
		2	20.0	2		<0.0001
	Japanese barberry	6	6.4	3	6.44	(<0.0001)
9	maple-leaf viburnum	3	4.3	6	8.17	
		2	12.0	0.5		0.0007
	common barberry	3	6.6	7	9.94	(0.0166)
		2	13.3	1		
10	black huckleberry	6	4.5	22	4.50	<0.0001
	Japanese honeysuckle	3	5.1	2	7.67	(<0.0001)
		2	10.3	0.2		
11	highbush blueberry	3	6.4	7	6.35	0.9833
	Louis' swallow-wort	6	6.3	18	6.34	(1.0000)
12	northern bayberry	6	5.3	10	5.34	0.1208
	scotchbroom	6	6.1	21	6.05	(0.9400)
13	grape	3	4.4	6	6.67	
		2	8.9	0.1		0.0814
	oriental bittersweet	3	3.7	19	5.78	(0.8475)
		2	7.8	1		
14	pasture rose	3	4.0	6	6.99	
		2	10.0	0.2		<0.0001
	multiflora rose	3	13.0	4	12.14	(<0.0001)
		1	11.3	–		
15	wrinkleleaf goldenrod	3	6.4	7	9.79	
		2	13.2	2		0.0080
	roundleaf greenbrier	6	8.5	19	8.49	(0.1741)
16	whitegrass	3	3.6	5	5.38	
		2	7.2	2		0.4226
	Japanese knotweed	3	3.4	5.2	5.79	(1.0000)
		2	8.2	2		

(*Continued*)

Table 2. (Continued)

Pair no.	Species	N		Initial sample mass		Significance at 0.05
			Mean (g)	COV (%)	Mean (g)	
17	interrupted fern	3	3.3	16	4.76	
		2	6.3	4		<0.0001
	purple loosestrife	3	4.7	6	7.17	(<0.0001)
		2	9.7	2		
18	reindeer lichen	6	10.6	7	10.56	<0.0001
	common sheep sorrel	6	5.1	18	5.09	(<0.0001)
19	sphagnum moss	6	8.7	11	8.68	<0.0001
	Japanese stiltgrass	3	2.4	15	3.47	(<0.0001)
		2	4.5	0.3		
20	three-lobed bazzania	6	13.6	12	13.62	<0.0001
	climbing nightshade	3	3.9	7	5.36	(<0.0001)
		2	6.8	1		
21	Schreber's big red stem moss	6	5.7	19	5.67	0.2430
	garlic mustard	6	5.1	26	5.14	(0.9976)

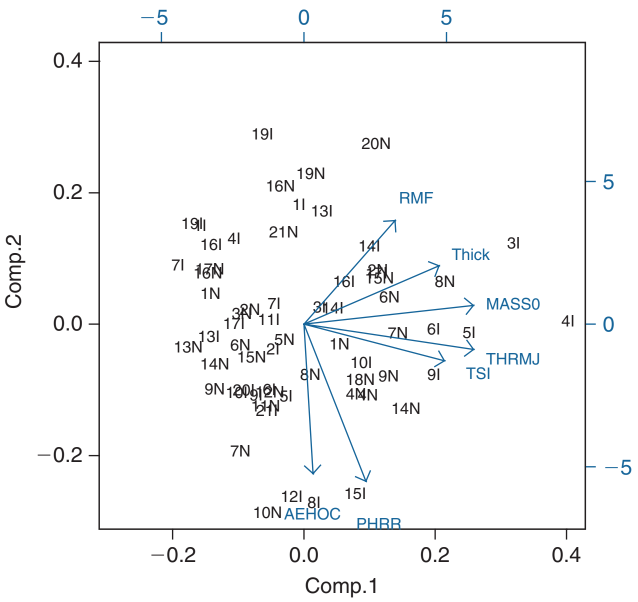

Fig. 2. Biplot of the first two principal components axes. Vectors are AEHOC (average effective heat of combustion), MASS0 (initial sample mass), PHRR (peak heat release rate), RMF (residual mass fraction), THRMJ (total heat release of the sample), TSI (time to sustained ignition), and Thick (sample thickness); units are provided in the text. Observations are the species pair numbers of Table 1 and represent an average for 2–6 replicates; I = Invasive, N = Non-invasive. Repeated symbols indicate multiple tests but with different initial sample mass and thickness (e.g. Series 1 *v.* Series 3) for the same species.

viburnum, pasture rose, and whitegrass, had differences with *P*-values <0.05. In an analysis of covariance, with initial mass as a covariate, the test for a non-zero relationship of AEHOC to initial mass (with common underlying slope) had a marginal *P*-value of 0.0556. As this was also supported in the principal component analysis, initial mass was not included in the model for which the comparisons were made.

Among species pairs (Table 3), AEHOC was significantly higher for invasive Japanese barberry than for non-invasive southern arrowwood. It was marginally higher for invasive roundleaf greenbrier than for wrinkleleaf goldenrod, and for invasive climbing nightshade than for three-lobed bazzania. AEHOC was significantly higher for non-invasive than for invasive species in the cases of: red maple *v.* Norway maple, pitch pine *v.* black locust, speckled alder *v.* glossy buckthorn, black huckleberry *v.* Japanese honeysuckle, and reindeer lichen *v.* common sheep sorrel (Table 3). We found a significant difference in AEHOC between all non-invasive plants *v.* all invasive plants (Table 4, $P\text{-value}_{adj} = 0.0154$). By growth form, AEHOC was significantly higher overall for non-invasive species. Non-invasive trees had higher AEHOC than invasive trees, but invasive vines had higher AEHOC than non-invasive vines (Table 4).

Regarding field data from actual situations, for species we tested that were present at four sites, AEHOC of non-invasive species was significantly higher than that of invasive species at two sites (Table 5). For all sites, the mean AEHOC for non-invasive species was slightly higher than that for the invasive species present.

Total heat release

Because the amount of test material was not controlled, the results for the THR are reported as the total heat release divided by the initial sample mass (Tables 3 and 4). The THR for the individual tests ranged from 2.3 to 32.7 MJ kg^{-1} with an overall average of 11.5 MJ kg^{-1}. The RMF (data not shown) is one distinction between the AEHOC based on mass loss and the THR calculated using initial mass. The average RMF was 10.6% and the maximum measured was 33.3%.

Mean THR was significantly greater for non-invasive trees than for invasive trees but otherwise did not differ by growth form (Table 4). Among species pairs (Table 3), invasive species had significantly higher values for THR than the non-invasive species in the cases of three species pairs: Japanese barberry *v.* southern arrowwood, climbing nightshade *v.* three-lobed bazzania, and garlic mustard *v.* Schreber's big red stem moss. For five other species pairs, non-invasive species had

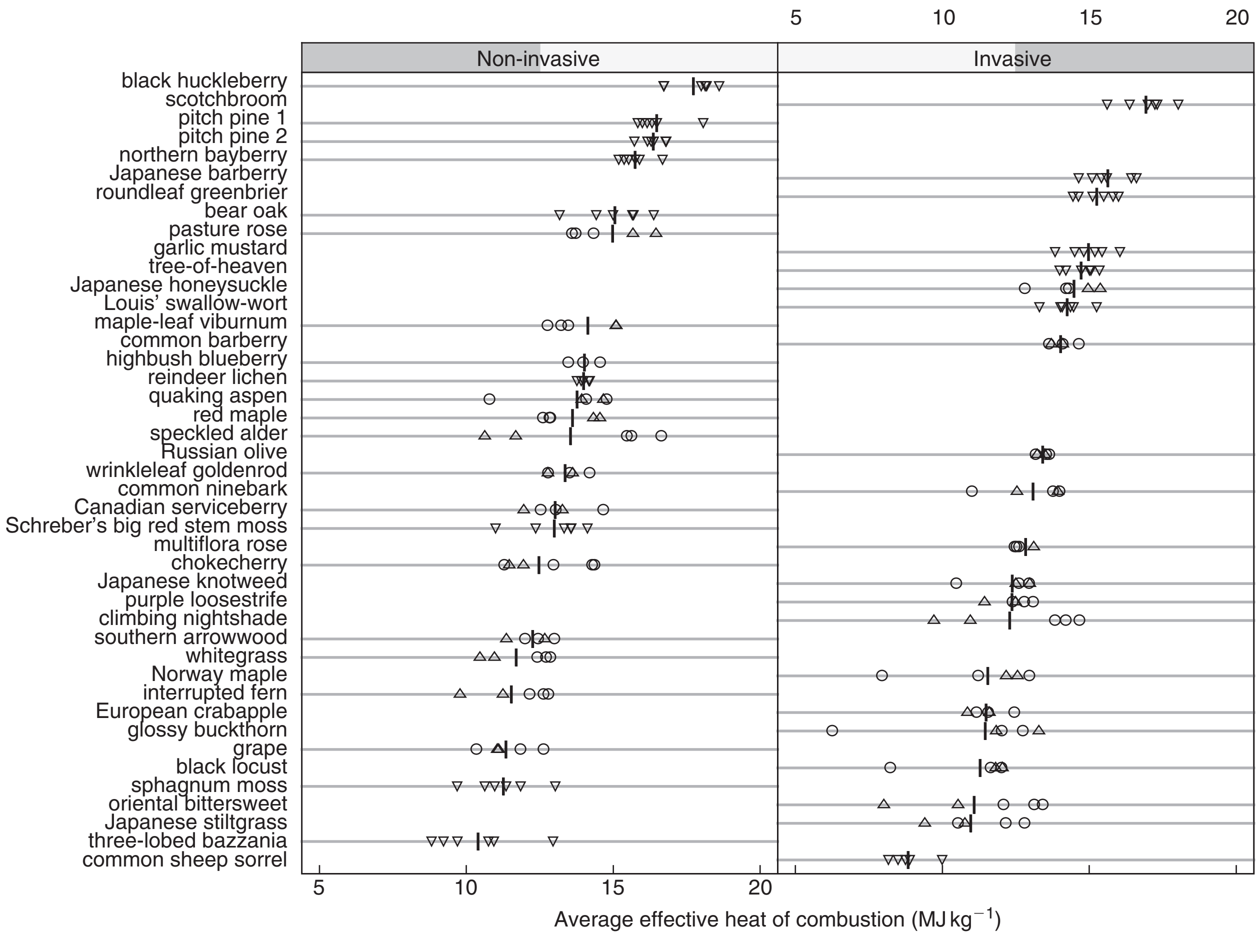

Fig. 3. Plot of average effective heat of combustion (AEHOC) for species sampled in the present study. Circles and triangles represent different sample series within a species. The bar on each line represents the least square mean estimate for that species.

higher values for THR than their invasive counterparts in the cases of red maple *v.* Norway maple, pitch pine *v.* black locust, black huckleberry *v.* Japanese honeysuckle, pasture rose *v.* multiflora rose, and reindeer lichen *v.* common sheep sorrel.

Peak heat release rate

The PHRR for the individual tests occurred from 21 to 336 s after initiation of radiant exposure. The PHRR for the individual tests ranged from 30 to 397 kW m^{-2} with an overall average of 138 kW m^{-2}. In a graphic portrayal of the PHRR data by species and by status as non-invasive and invasive (Fig. 4), three invasive species had high average values – Japanese barberry was highest, followed by roundleaf greenbrier and scotchbroom. Three other invasive species had the lowest average values – common sheep sorrel, Japanese stiltgrass and Norway maple. Three species that grow in fire-adapted forest types had high PHRR – black huckleberry, pitch pine, and reindeer lichen. Non-invasive speckled alder usually grows in mesic or wet sites, and had relatively high PHRR. Invasive garlic mustard had relatively high PHRR. The apparent standard deviations differed widely.

Most species that were tested at multiple thicknesses did not exhibit differences in PHRR based on thickness differences. However, climbing nightshade had very significant differences (P-value <0.01), and several had significant differences (P-value <0.05). The test of initial mass as a helpful covariate (common slope) was not significant.

These PHRR results and the principal component analysis did not indicate that the initial sample mass was a consistent factor in the PHRR. Unweighted linear regression of PHRR with AEHOC resulted in a model with an R^2 of 0.45. Adding the initial sample mass to the model increased the R^2 of the model to only 0.49. The linear regression of PHRR with just the initial sample mass resulted in an R^2 of 0.02.

Mean PHRR did not differ by growth form based on linear contrasts (not shown), but was significantly higher for some non-invasive species than for their paired invasive species, e.g. pitch pine had higher PHRR than black locust, speckled alder than glossy buckthorn, and reindeer lichen than common sheep sorrel (Fig. 4). PHRR was higher for some invasive species than for their paired non-invasive counterparts: Japanese barberry had greater PHRR than southern arrowwood, scotchbroom than northern bayberry, roundleaf greenbrier than wrinkleleaf goldenrod, and garlic mustard than Schreber's big red stem moss. PHRR was slightly higher for non-invasive black huckleberry than for invasive Japanese honeysuckle.

Table 3. Average Effective Heat of Combustion (AEHOC) and Total Heat Release (THR) of the cone calorimeter samples

Listed by species pair, species, number of replicates, mean for sample, percentage covariance, mean for species, and linear contrast test results for difference between non-invasive and invasive species. Average effective heat of combustion is the total heat release divided by the mass loss. Significance values are the unadjusted comparison-wise error rate and, in parentheses, the simultaneous error rate (to avoid false positives when conducting numerous comparisons). Each invasive plant was paired with a non-invasive plant. The non-invasive plant is listed first. N, Number of samples tested

Pair no.	Species	N	AEHOC				THR			
			Mean (MJ kg^{-1})	COV (%)	Mean (MJ kg^{-1})	Significance at 0.05	Mean (MJ kg^{-1})	COV (%)	Mean (MJ kg^{-1})	Significance at 0.05
1	red maple	3	12.8	1	13.61		12.11	6.43	12.59	
		2	14.4	1		0.0015	13.08	0.87		0.0009
	Norway maple	3	10.7	24	11.54	(0.0411)	10.14	31.66	10.10	(0.0220)
		2	12.4	2			10.07	0.56		
2	quaking aspen	3	13.2	16	13.76		12.01	22.32	12.07	
		2	14.3	4		0.1156	12.14	5.47		0.0754
	tree-of-heaven	6	14.7	4	14.72	(0.9415)	13.32	5.31	13.32	(0.8229)
3	chokecherry	4	13.2	11	12.47		11.96	5.66	10.95	
		2	11.7	3		0.1130	9.94	5.03		0.1905
	European crabapple	3	11.7	6	11.48	(0.9379)	10.68	6.73	10.01	(0.9898)
		2	11.2	5			9.34	5.22		
4	pitch pine 1	6	16.5	5	16.47		14.11	8.87	14.11	
	pitch pine 2	6	16.4	2	16.36	<0.0001	13.77	4.34	13.77	<0.0001
	black locust	3	10.6	20	11.28	(<0.0001)	9.45	14.04	9.94	(<0.0001)
		2	11.9	1			10.43	4.98		
5	bear oak	6	15.1	8	15.05	0.0074	13.64	6.60	13.64	0.0804
	Russian olive	3	13.5	2	13.41	(0.1764)	13.16	2.79	12.41	(0.8427)
		2	13.4	1			11.66	0.65		
6	Canadian serviceberry	3	13.4	8	13.02		12.74	10.06	11.91	
		2	12.6	7		0.9159	11.08	7.29		0.7782
	common ninebark	3	12.9	13	13.08	(1.0000)	12.64	10.74	12.11	(1.0000)
		2	13.2	7			11.58	7.79		
7	speckled alder	3	15.9	4	13.54		15.57	4.60	12.88	
		2	11.2	7		0.0013	10.19	0.96		0.0359
	glossy buckthorn	3	10.4	34	11.45	(0.0374)	10.43	38.78	11.32	(0.5632)
		2	12.6	8			12.21	1.46		
8	southern arrowwood	3	12.5	4	12.25		12.10	4.84	11.48	
		2	12.0	8		<0.0001	10.87	3.22		<0.0001
	Japanese barberry	6	15.6	5	15.63	(<0.0001)	14.55	6.41	14.55	(0.0004)
9	maple-leaf viburnum	3	13.2	3	14.13		13.69	4.05	13.64	
		2	15.1	0.05		0.8633	13.59	1.70		0.4686
	common barberry	3	14.1	4	14.02	(1.0000)	13.63	3.72	13.11	(1.0000)
		2	13.9	2			12.58	0.29		
10	black huckleberry	6	17.7	4	17.73	<0.0001	17.09	7.87	17.09	<0.0001
	Japanese honeysuckle	3	13.8	6	14.48	(<0.0001)	13.45	6.41	13.39	(<0.0001)
		2	15.2	2			13.33	2.68		
11	highbush blueberry	3	14.0	4	14.01	0.7407	13.66	3.53	13.66	0.1573
	Louis' swallow-wort	6	14.2	4	14.25	(1.0000)	12.52	8.34	12.52	(0.9758)
12	northern bayberry	6	15.7	3	15.74	0.0389	14.47	7.94	14.47	0.0213
	scotchbroom	6	16.9	5	16.92	(0.6174)	15.99	7.99	15.99	(0.3922)
13	grape	3	11.6	10	11.35		12.33	10.70	10.66	
		2	11.1	0.3		0.6737	8.99	5.38		0.8537
	oriental bittersweet	3	12.9	5	11.08	(1.0000)	12.52	6.94	10.52	(1.0000)
		2	9.3	19			8.53	16.55		
14	pasture rose	3	13.9	3	14.98		13.33	3.83	13.47	
		2	16.1	3		0.0036	13.61	7.63		0.0014
	multiflora rose	3	12.5	1	12.83	(0.0917)	10.91	3.45	10.74	(0.0337)
		1	13.1	–			10.57	–		
15	wrinkleleaf goldenrod	3	13.5	5	13.36		12.63	8.13	11.95	
		2	13.2	4		0.0021	11.26	5.13		0.0043
	roundleaf greenbrier	6	15.2	4	15.25	(0.0575)	13.96	3.97	13.96	(0.0998)
16	whitegrass	3	12.7	2	11.69		11.38	5.52	10.32	
		2	10.7	3		0.2852	9.26	13.61		0.4978
	Japanese knotweed	3	12.0	11	12.38	(0.9994)	10.79	15.62	10.82	(1.0000)
		2	12.7	3			10.84	2.70		

(*Continued*)

Table 3. (Continued)

Pair no.	Species	N	AEHOC				THR			
			Mean (MJ kg^{-1})	COV (%)	Mean (MJ kg^{-1})	Significance at 0.05	Mean (MJ kg^{-1})	COV (%)	Mean (MJ kg^{-1})	Significance at 0.05
17	interrupted fern	3	12.5	3	11.53		11.12	1.14	9.51	
		2	10.5	10		0.1934	7.91	12.58		0.0455
	purple loosestrife	3	12.8	3	12.36	(0.9926)	11.86	2.91	10.99	(0.6477)
		2	12.0	6			10.13	2.37		
18	reindeer lichen	6	14.0	1	13.99	<0.0001	13.50	3.03	13.50	<0.0001
	common sheep sorrel	6	8.8	7	8.84	(<0.0001)	6.63	14.38	6.63	(<0.0001)
19	sphagnum moss	6	11.3	10	11.25	0.6315	9.38	12.91	9.38	0.7589
	Japanese stiltgrass	3	11.8	10	10.96	(1.0000)	10.28	13.05	9.17	(1.0000)
		2	10.1	10			8.05	2.80		
20	three-lobed bazzania	6	10.4	14	10.40	0.0021	7.95	17.23	7.95	0.0002
	climbing nightshade	3	14.2	3	12.29	(0.0570)	13.32	3.90	10.57	(0.0057)
		2	10.3	8			7.82	17.88		
21	Schreber's big red stem moss	6	13.0	9	12.99	0.0007	11.08	13.14	11.08	<0.0001
	garlic mustard	6	15.0	5	14.97	(0.0198)	14.01	7.80	14.01	(0.0004)

Table 4. Mean Average Effective Heat of Combustion (AEHOC) and Total Heat Release (THR) of the cone calorimeter samples by growth form, compared in linear contrasts

Comparison	Non-invasive estimate (MJ kg^{-1})	Invasive estimate (MJ kg^{-1})	Difference estimate (MJ kg^{-1})	s.e. (difference) (MJ kg^{-1})	T-value	*P*-value	Adj. *P*-value
			AEHOC				
Overall	13.49	13.01	0.48	0.1354	3.54	0.0005	0.0154
Trees	14.26	12.26	2.01	0.2859	7.01	<0.0001	<0.0001
Shrubs	14.42	14.07	0.35	0.227	1.54	0.1249	0.9535
Vines	11.35	13.27	−1.92	0.5166	−3.71	0.0003	0.0088
Herbs	12.17[A]	11.97	0.21	0.2396	0.87	0.3876	0.9999
			THR				
Overall	12.20	11.72	0.47	0.1558	3.04	0.0028	0.0670
Trees	12.64	10.84	1.80	0.3290	5.46	<0.0001	<0.0001
Shrubs	13.57	13.03	0.55	0.2612	2.1	0.0370	0.5742
Vines	10.66	12.14	−1.49	0.5945	−2.5	0.0134	0.2708
Herbs	10.53[A]	10.37	0.16	0.2757	0.58	0.5612	1.0000

[A]Includes a native moss, liverwort and lichen species.

Time for sustained ignition

The TSI for the individual tests ranged from 15 to 203 s. In a graphic portrayal of the TSI by species and by status as non-invasive and invasive (Fig. 5), we found relatively short ignition times for invasive Japanese stiltgrass, glossy buckthorn, Louis' swallow-wort and Norway maple. Black locust, roundleaf greenbrier, common ninebark and common barberry (all are invasive species) had long ignition times. For 13 samples, sustained ignition of the test sample was not observed. These included all six samples of common sheep sorrel (Fig. 5). For the other seven samples of four species, the samples for which no sustained ignition was observed were ones in which the initial sample mass had been approximately doubled from that originally tested. We used a criterion that the observation of sustained flames required the flames to be sustained for at least 10 s. Although sustained flames were not recorded, intermittent spot flames were observed in the tests of common sheep sorrel.

TSI appears to exhibit increasing variability with increased mean values (non-normal behaviour), indicating that survival-type models may help us understand this response better in the future. Survival-type models typically model lifetime and reliability data either parametrically or non-parametrically by accounting for heterogeneity and incorporating censoring mechanisms such as occurred with TSI (Lawless 2003).

In accord with the principal component analysis, statistical analysis indicated a correlation between the TSI and the initial sample mass. Unweighted linear regression of TSI with initial sample mass (shown as MASS0 in Fig. 2) resulted in an R^2 of 0.23 for the model. Adding the average mass loss rate (for duration of test) to the model increased the R^2 to 0.31. This result is consistent with the expectation that the volume of volatile gases contributes to sustained ignition. There was also a correlation between the average mass loss rate and AEHOC ($R^2 = 0.22$) but not between TSI and AEHOC ($R^2 = 0.02$). The model of TSI with MASS0 and AEHOC had an R^2 of 0.26.

Mean TSI (data not shown) differed for only two of the 21 species pairs, and did not differ by growth form. Time was significantly higher for invasive black locust than for pitch pine and was slightly higher for invasive roundleaf greenbrier than for non-invasive wrinkleleaf goldenrod.

Table 5. Average Effective Heat of Combustion (AEHOC) for non-invasive *v.* invasive species that co-occur at four sites and four forest types

Fuels were reported by Dibble and Rees (2005), but data are lacking regarding actual displacement of non-invasive species by invasive plants at these sites. Numerous other native, non-invasive species were present at all sites but were not sampled for combustion characteristics

Forest type	Site	Non-invasive species	Invasive species	AEHOC for non-invasive species ($MJ\,kg^{-1}$)	AEHOC for invasive species ($MJ\,kg^{-1}$)	Difference ($MJ\,kg^{-1}$)	P-value$_{unadj}$
Pitch pine (fire-adapted type, with scrub oak, which is vulnerable to stand conversion by black locust)	Albany Pine Bush Preserve, Albany, NY	red maple, Canadian serviceberry[B], black huckleberry, whitegrass, pitch pine, quaking aspen, chokecherry, scrub oak, pasture rose, wrinkleleaf goldenrod, maple-leaf viburnum	garlic mustard, Oriental bittersweet, bush honeysuckle[A], black locust, common sheep sorrel, bittersweet nightshade	14.20	12.15	2.05	<0.0001
Mixed woods (northern hardwood with eastern white pine, white spruce)	Merck Forest and Farmland Center, Rupert, VT	red maple, Canadian serviceberry[B], interrupted fern, quaking aspen, chokecherry, wrinkleleaf goldenrod	Russian olive[C], bush honeysuckle[A], European crabapple, multiflora rose, bittersweet nightshade	12.96	12.90	0.06	0.8259
Softwoods (red spruce–balsam fir with eastern white pine and some hardwoods)	Rachel Carson National Wildlife Refuge, Brave Boat Harbor Division, Kittery, ME	red maple, Canadian serviceberry[B], black huckleberry, northern bayberry, quaking aspen, chokecherry, wrinkleleaf goldenrod, highbush blueberry, maple-leaf viburnum, arrowwood, grape	Japanese barberry, common barberry, Oriental bittersweet, glossy buckthorn, European crabapple, multiflora rose	13.77	12.75	1.02	<0.0001
Hardwoods (northern red oak–red maple–bigtooth aspen in former apple orchard)	Penobscot Experimental Forest, Bradley, ME	red maple, speckled alder, Canadian serviceberry[B], interrupted fern, quaking aspen, chokecherry, highbush blueberry, maple-leaf viburnum, southern arrowwood	Norway maple, Japanese barberry, glossy buckthorn, bush honeysuckle[A], European crabapple, bittersweet nightshade	13.15	12.81	0.34	0.16

[A] Heat content data for Japanese honeysuckle were used, though the *Lonicera* species found at these sites were invasive bush honeysuckle (including *Lonicera morrowii*).
[B] Heat content data for Canadian serviceberry, *Amelanchier Canadensis*, were used, though plants observed in the field lacked sufficient material to identify to species.
[C] Heat content data for Russian olive were used though in the field we identified autumn olive, *Elaeagnus umbellata*.

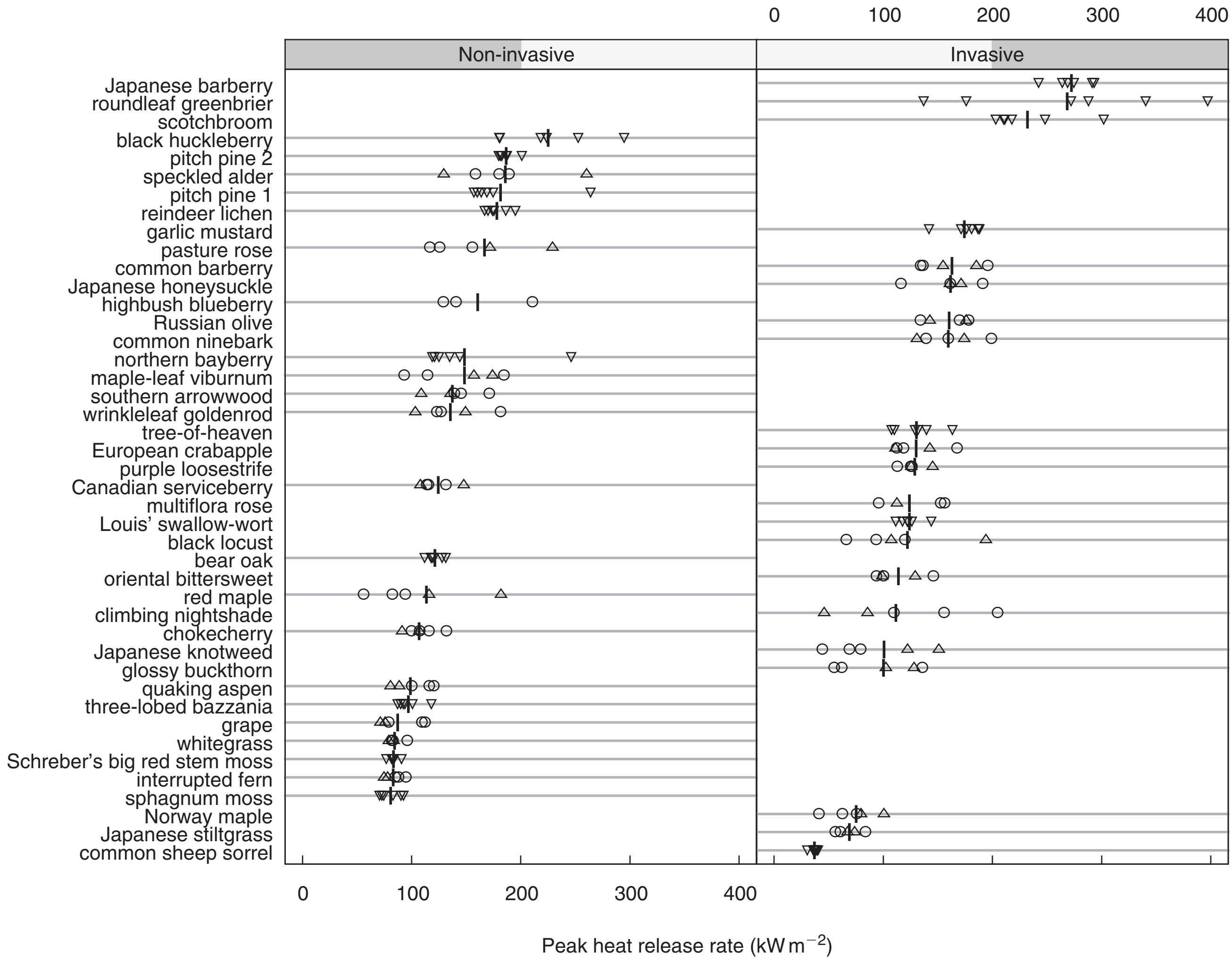

Fig. 4. Plot of peak heat release rate (PHRR) for species sampled in the present study. Circles and triangles represent different sample series within a species. The bar on each line represents the least square mean estimate for that species.

Discussion

We have placed more emphasis on the AEHOC data because of the possibility that differences in initial mass would influence the responses quantified in other variables. Also, AEHOC is not a result that is expressed on a 'per surface area' basis. The result of a significant difference overall in AEHOC between non-invasive *v.* invasive plants could reflect some previously unexplored attributes of the species used in the current study. Several native, non-invasive species that grow on sandy soils in fire-adapted ecosystems, such as pitch pine, black huckleberry and northern bayberry, had especially high values for AEHOC (Table 3, Fig. 3). Over all 42 species, many of the invasive species had lower AEHOC levels than their non-invasive counterparts. Invasive non-native species with especially low AEHOC (Table 3, Fig. 3) included oriental bittersweet, Japanese stiltgrass, black locust, glossy buckthorn, European crabapple, Norway maple and common sheep sorrel; their presence as large patches of vegetation on the landscape could decrease fire return interval and fire intensity if they invade fire-adapted ecosystems. Although this might make fire protection less problematic, it represents the loss of native plant communities and perhaps some of the associated rare plants and animals that depend on frequent fire.

We found lowest values for AEHOC in common sheep sorrel (8.8 MJ kg^{-1}). This agricultural weed can colonise forest openings occupied by reindeer lichen (14.0 MJ kg^{-1}) in some conifer forests and mixed woods in the north-eastern USA. The AEHOC and the other cone calorimeter data suggest that a ground fire might not spread as quickly or be as intense where common sheep sorrel has become abundant as could happen when lichen cover is intact. Whether or not the natural fire regime might be altered when the ecosystem has been degraded by invasion of common sheep sorrel, fuel moisture is expected to supersede effects due to heat content.

In another scenario, invasive species with relatively high values for AEHOC, including scotchbroom, Japanese barberry, tree-of-heaven, Japanese honeysuckle, swallow-wort and garlic mustard, could alter the fuel characteristics in a natural area where dominant plants include whitegrass, interrupted fern, grape, southern arrowwood, sphagnum moss, and three-lobed

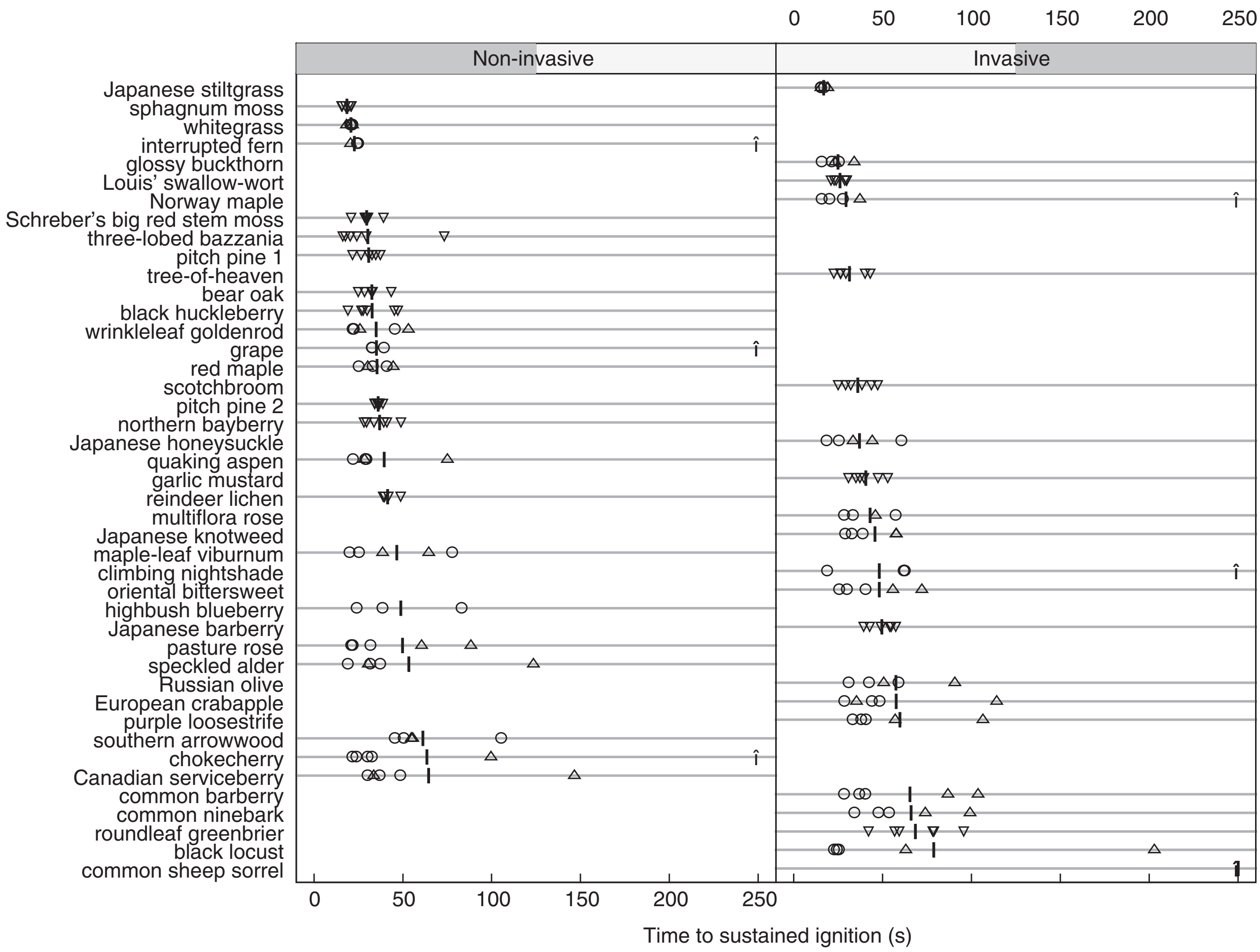

Fig. 5. Plot of times for sustained ignition (TSI) for species sampled in the present study. Circles and triangles represent different sample series within a species. The bar on each line represents the least square mean estimate for that species. Data at 250 s are for specimens for which there was no observation of sustained ignition.

bazzania – all of which have low AEHOC. In such a case, fire hazard would become greater in the presence of abundant invasive plants than when such plants are not present, based on our data.

AEHOC is independent of other features that affect flammability, including fuel moisture, arrangement of fuels in three dimensional space, and phenology. These other factors must be accounted for in projecting flammability potential for a fuel bed or whole plant. For example, we might expect that regardless of overstorey composition, a forest shrub layer occupied by viburnum, alder and shadbush would have different fire behaviour than if the stand had a dense population of multiflora rose, partly because this non-native invasive rose is capable of climbing into trees to more than 6 m high (A. C. Dibble, unpub. data). Japanese honeysuckle is likewise capable of forming a substantial ladder fuel. In an extreme drought, Oriental bittersweet is likely to present a ladder fuel even though its heat content as measured in AEHOC is low compared with most other species we sampled.

In previous studies (cited in White *et al*. 2002), the ranking of results from the cone calorimeter testing of samples of foliage and twigs was generally consistent with flammability recommendations for whole plants in the available literature. Of the plants tested in the present study, scotchbroom, Japanese honeysuckle, quaking aspen, and black locust were listed in the University of California (UC) database[2] (Lubin and Shelly 1997), which is a compilation of recommendations in available references. In that list, Japanese honeysuckle was not recommended for use in fire-prone environments, and we found it to have high AEHOC (14.5 MJ kg^{-1}) in the current study. Scotchbroom was also not recommended by references in the database and it also has a high AEHOC (16.9 MJ kg^{-1}). Black locust was recommended by references in the UC database, and we found it to have low AEHOC (11.3 MJ kg^{-1}). In the database at www.usda.plants.gov/ (accessed 30 Oct 2006), California is noted as having listed black locust as invasive, so there is a

[2] This database was previously on the website of the University of California Forest Products Laboratory (http://www.ucfpl.ucop.edu/491/Garden/PlantList.htm, accessed 6 January 2004). With the closure of this laboratory, some of the information was moved to the website of Dr. Frank Beall (http://nature.berkeley.edu/∼fbeall/FireMit/HODefSpaceGuide.pdf, accessed 30 Oct 2006).

trade-off between reducing the flammability of landscape plantings in fire-prone areas and risking spread of invasive pest plants. In that list, quaking aspen was recommended for use in fire-prone environments in the UC database and in the present study, we found it to have intermediate AEHOC (13.8 MJ kg^{-1}). Prescribed fire in quaking aspen stands often is constrained by seasonality and lack of ground fuels (Howard 1996). A possible relationship between physical characteristics and the levels of AEHOC that we found for quaking aspen in this present study is not known.

In our results, the ranking of vegetation by AEHOC, PHRR and TSI (Figs 3–5) were not consistent. In particular, the correlation of the rankings based on the TSI with those based on AEHOC ($R^2 = 0.001$) and PHRR ($R^2 = 0.14$) were low. The correlation of the rankings based on PHRR with that based on AEHOC had an $R^2 = 0.64$. The results can be ascribed to different aspects of the flammability of the vegetation and possibly the effect of the initial sample mass on the TSI in the cone calorimeter. The AEHOC more reflects the heat released during the entire test. In addition to being affected by other factors such as the physical characteristics of the foliage, the TSI is affected by the initial release of volatiles. The PHRR also reflects the initial reaction of the material to fire exposure. In addition to AEHOC, the rankings for PHRR and TSI should also be considered when evaluating the relative fire behaviour of particular species.

There are methodological matters that need further refinements before the cone calorimeter can be widely used for measurements of the fire behaviour characteristics of foliage and twigs. The amount of test material is relatively small. Although the 100 by 100 mm-sample holder allowed us to test unground samples, most results normally reported for the cone calorimeter are expressed on a square meter basis. Because the unground material does not completely cover the surface area of the sample holder, the assumed exposed surface area of such results is artificial and only applicable to the cone calorimeter. The question of the exposed surface area of the vegetation sample complicates any attempt to use a consistent initial sample mass in the tests. Further work is needed to clarify the question of the effect of the physical characteristics of the test sample, such as mass and thickness, on the test results. In his discussion of his model, Rothermel (1994) hypothesised that low values of fire intensity and rate of spread occur at two extremes of compactness and that the optimum arrangement would not be the same for different sizes of fuel particles. Such a non-linear relationship could explain our evidence that sample mass has an effect in some samples, but we did not make a consistent correction for sample mass. Generally, we tested only two levels of sample mass per species. Of the results reported, TSI is the variable most likely to be affected by the initial sample mass. When using log(TSI), initial mass becomes highly significant covariate ($P = 0.0019$) but if left untransformed, it is marginal. The AEHOC is least likely to be affected. Further modelling of TSI could elucidate differences.

In the present study, we tested pre-dried samples. Thus fuel moisture content was not accounted for in the rankings from the cone data. If an invasive species alters the moisture content of live and dead fuels for a portion of the landscape, this could affect fire hazard. Indeed, some non-native plants leaf out earlier than native counterparts and retain their leaves later into the autumn, e.g. Japanese barberry, oriental bittersweet, glossy buckthorn and Asian honeysuckle (represented in the current study by Japanese honeysuckle, a vine). Fuel moisture is usually found to be the most important factor contributing to flammability, whether plant fuels are simulated or ignited. A standardised live fuel moisture sampling protocol is currently under development by the San Dimas Technology Development Center, based on Countryman and Dean (1979) (D. Weiss, pers. comm.). White *et al*. (1996) and Weise *et al*. (2005) found that PHRR, measured with a cone calorimeter, of oven-dry live fuels was 2–3 times as great as for the same live fuels when green. The AEHOC of the oven-dry samples ranged from 13 to 19 MJ kg^{-1} and from <1 to 12 MJ kg^{-1} for the same species when green. In tests using 50 kW m^{-2} incident heat flux, Enninful and Torvi (2005) found that samples of jack pine conditioned at 73% relative humidity (RH) had an average heat release rate 8% less than the average heat release rate for samples conditioned at 23% RH. Dimitrakopoulos and Papioannou (2001) used a cone heater (ISO 5657–1986E) like the one in a cone calorimeter in their study of time-to-ignition for dominant forest fuels in the Mediterranean region. Their samples varied in moisture content from air-dry to fresh foliage, and they found that moisture content contributed to fuel flammability more than any other factor. Weise *et al*. (1998) evaluated the adequacy of selected live fuel sampling efforts and found that variability of live fuel moisture ranged considerably between species and sampling efforts. In some instances, a 95% confidence interval for mean live fuel moisture covered the entire range of data (60–120%) in which fire managers made decisions based on live fuel moisture. Suggested sample sizes for different allowable sampling errors were presented. That work was an outgrowth of the development of a proposed west-wide fuel moisture sampling program that was recommended by the Interagency Management Review Team following the 1994 fire season (Cohen *et al*., unpub. data; Weise and Saveland 1996).

Our data on the relative combustion characteristics of foliage and twigs could serve as part of a new information bank useful for determining whether the average combustibility assumptions in a model are valid for a particular species. Wider application will require the development of a corresponding fire model that uses combustion characteristics as measured in the cone calorimeter among the input variables. There remains a gap regarding translation of cone calorimeter results to prediction of fire behaviour in the field. Fire practitioners across the USA need improved fire behaviour models, as they are limited by the assumptions and generalisations needed to run the model. With more relevant inputs on combustion characteristics of the dominant species in fuel beds these practitioners encounter, the reliability and usefulness of fire behaviour models might increase. Toward this goal, more work should be done to further investigate the potential for the cone calorimeter to provide improved combustion characterisation of the foliage and twigs.

Another potential application is in the selection and promotion of plantings that decrease the flammability of fire breaks. Green strips of less flammable vegetation around priority zones as recommended by Hogenbirk and Sarrazin-Delay (1995) would be based in part on combustibility data.

Another new tool which could be enhanced by improved data is the Fuel Characteristic Classification System (FCC), which provides managers with a comprehensive set of fuelbeds and fuel class potentials, enabling the assignment of fuel properties on landscapes for major vegetation types across the USA (Ottmar *et al*. 2003). This clearinghouse for fuels data does not use the information outright. The system provides several output format options allowing input into general fuel consumption, fire effect, and fire behaviour models. Supporting the software system is a large data library, which warehouses fuels information including the fuel bed prototypes, biomass equations, physiognomic features, and physical, chemical and structural fuel parameters. As fuel characteristics information is gathered regarding the manner in which a specific fuel burns, the information can easily be entered into the FCC database and become available to users. For example, heat content values, bulk densities, specific gravities, and SAV ratios are important fuel characteristics that are needed to successfully run fire behaviour and fire effects models.

We anticipate that with more studies of the kind we report here, some resolution will emerge regarding standardised approaches to quantifying fuel combustion and flammability characteristics. An effort toward standardised test protocols for flammability characteristics could lead to improved data for modelling fire behaviour in general, and would enhance existing knowledge as presented in the Fire Monitoring Navigator of the Bureau of Land Management (Stock *et al*. 1997) and the US Department of the Interior Fire Monitoring Handbook (US Department of Interior, National Park Service 2001).

Conclusion

Timing and intensity of fuel treatments could depend on fuel characteristics that are probably altered when invasive plants are dominant among or have displaced native, non-invasive plant communities. We found relatively high AEHOC in some non-native invasive species that form dense vegetation in the north-eastern USA, including Japanese barberry, tree-of-heaven, garlic mustard, common barberry, swallow-wort, scotchbroom and Japanese honeysuckle. These species present a challenge because their eradication is expensive and labour intensive, if it is possible at all. Their presence in forests and overgrown fields represents a live fuel load that could be problematic in dry conditions if they also produce enough biomass to release more heat, overall, than the natural vegetation under the same conditions. Crowning and replacement fires could be more likely where these invasive species comprise a large proportion of the fuel bed. Conversely, fire-adapted ecosystems in the north-eastern USA could be severely degraded if fuel beds are occupied by black locust, Norway maple, or glossy buckthorn. Data from the cone calorimeter bring some of these fuel relationships into better understanding and could improve efficacy of fire behaviour modelling in the region. The extrapolation of data for foliage and twigs to whole plants or the field requires that one also consider the size, shape, and spatial distribution of the fuel being evaluated.

Acknowledgements

The present study was funded by the Joint Fire Science Program, Boise, ID, as part of a project titled 'Fire management options to control woody invasive plants in the north-eastern and the mid-Atlantic USA', with Principal Investigators Alison C. Dibble and William A. Patterson III. We appreciate field help from Catherine A. Rees and the conducting of cone calorimeter tests by Anne M. Fuller. William A. Patterson III and Mark J. Ducey contributed comments on the study design. David Weise and Alan J. Long provided comments on an earlier version of the manuscript. KellyAnn Gorman provided a perspective on practical application of the cone data. We thank the many landowners who permitted sampling of vegetation on their properties.

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Manuscript received 4 November 2005, accepted 14 February 2007