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RESEARCH ARTICLE

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Properties and flammability of major tree species in the Beijing area

Abstract In order to examine correlations among the properties of tree species and to quantify the relationships between these properties and flammability, the properties of 20 tree species, consisting of heat of combustion, extractive contents, ash content, moisture content and basic density, were measured via experimental methods. In the first instance, the results show that, there are significant correlations between heat of combustion and extractive contents, ash content and basic density. Second, heat of combustion can be presented effectively in terms of linear regression models with extractive contents and ash content as independent variables. Third, a flammable model was developed based on four properties of tree species as independent variables, i.e., heat of combustion, extractive contents, ash content and moisture content. Finally, the flammability of 20 tree species is compared, ordered and ranked based on this flammable model. The conclusion is that flammability can be predicted from properties of tree species, which are significantly correlated among themselves.

Keywords tree species, properties, flammability

1 Introduction

Forests consist of several kinds of fuels, mainly consisting of trees as live fuel and litter as dead fuel. Trees are the key factor in crown fire initiation and spread, especially conifers with their effect on crown moisture and load. Floor litter consists of light fuels and in the case of forest fires act as flammable fuel, produced from leaves and branches. Flammability varies with tree species and various forests have different tree species and vary in constituent proportions. Therefore, tree flammability is a basic condition in the evaluation of forest combustibility.

In recent decades, research in flammability has focused on the effect of fuel properties on this flammability. The relationship between fuel properties such as the heat of combustion, extractives content, ash content, moisture content and flammability of various tree species has been well documented as the main aspects of forest fires (Hu, 1995; Wang et al., 1996; Yu et al., 1998; Xie and Li, 1999; Kataki and Konwer, 2001, 2002; Zhang et al., 2001; Shanavas and Kumur, 2003; Chan et al., 2003; Liu and Hu, 2005). In addition, Schwilk (2003) concluded that dead branches in the canopy contributes to flammability. Bio-ecological characteristics, such as escape ratios of easily burning air, are also of concern (Chen et al., 1988; Wang et al., 1999; Zhang et al., 1999; Tian et al., 2002). Besides, fuel moisture content has been considered one of the most important variables in flammability and large-scale fire behavior modeling (Dimitrakopoulos and Papaioannou, 2001; Chuvieco et al., 2004; Gisborne, 2004). Therefore, properties of different tree species are important in the evaluation of tree flammability.

Our purpose was to determine the correlation among the properties of a number of tree species and to express these quantitatively. In addition, tree flammability is to be predicted from properties of tree species as variables.

2 Methods

2.1 Selection of tree species and samples

Twenty common tree species were studied, given their local importance. Most indigenous species were included. The species covered, both conifers and broad-leaved species as well as shrubs, were the following: *Pinus tabulaeformis* Carr., *Pinus armandii* Franch., *Platycladus orientalis* Franco, *Robinia pseudoacacia* L., *Koelreuteria paniculata* Laxm., *Syringa amurensis* Rupr., *Ulmus*

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pumila L., *Ailanthus altissima* Swingle, *Acer mono* Maxim., *Euonymus bungeanus* Maxim., *Quercus variabilis* BI., *Sophora japonica* L., *Fraxinus chinensis* Roxb., *Populus canadensis* Moench., *Cotinus coggygria* Scop., *Amygdalus davidiana* C., *Armeniaca sibirica* Lam., *Syringa oblata* Lindl., *Vitex negundo* var. *heterophylla* Rehd. and *Spiraea salicifolia* L.

Sampling was conducted in the Xishan Forest Farm and the Badaling Forest Farm, both located in the Beijing mountain area. The samples were collected in November. Trees become more flammable during this month, because of their lower fuel moisture content and because of higher wind speeds.

2.2 Experimental methods

2.2.1 Fuel moisture content

Leaves sampled were put in envelops as specimens and their fresh weights measured immediately. The specimens were then kept in an oven at 80 ± 2°C until a constant weight was reached. Fuel moisture content was computed as follows:

$$\mathrm{FMC} = \frac{(\mathrm{W_N} - \mathrm{W_A}) - (\mathrm{W_D} - \mathrm{W_B})}{\mathrm{W_D} - \mathrm{W_B}} \times 100\%$$

where FMC is the fuel moisture content (%), W_N the fresh weight of the specimen (g), W_D the oven-dry weight of the specimen (g), W_A the fresh weight of the envelop (g) and W_B the oven-dry weight of the envelop (g).

2.2.2 Extract content

One gram of oven-dried (80 ± 2°C) mashed samples were packed in filter paper and extracted after eight hours using Saxhlet equipment fitted with petroleum ether (60–90°C) and placed in a water bath at constant temperature (80°C). The extract content was calculated as follows:

$$E = \frac{W_B - W_A}{W}$$

where E is the extract content (g), W_B weight of the sample and filter paper before extraction (g), W_A weight of the sample and filter paper after extraction (g) and W weight of the sample before extraction (g).

2.2.3 Ash content

First, samples of 1 g of oven-dried (80±2°C) mashed material were placed in a Si-crucible, carbonized in the furnace until smoke emission stopped. Then the samples were burned in a Muffle furnace at 650°C for six hours. In the end, the ash content was calculated using the equation:

$$A = \frac{W_A - W_C}{W_B - W_C}$$

where A is the ash content (g), W_B the weight of the prepared sample and crucible (g), W_A the weight of resultant ash and crucible (g) and W_C the weight of the crucible (g).

2.2.4 Heat of combustion

Samples were dried in an oven at 80±2°C until a constant weight was obtained and then chipped separately into smaller sizes. One gram of the material was accurately weighted, compressed and its heat of combustion estimated, using a Parr 6300 Oxygen Bomb Calorimeter directly.

2.2.5 Basic density

Specimens (1 g) of oven-dried (80±2°C) mashed material were compressed. Then the compressed specimens were accurately weighted and the volumes measured with a Vernier caliper. Basic density was calculated as follows:

$$\rho = M/V$$

where ρ is the basic density (g/cm^3), M the oven-dry weight of the specimen (g) and V the volume of the specimen (cm^3).

2.3 Data analysis

The correlations and quantitative relationships among the properties of tree species were determined separately by correlation and linear regression analyses using SPSS13.0 for Windows software. Prediction models of flammability were quantified by principal component analysis and their flammable rank was obtained by cluster analysis.

3 Results

3.1 Correlation analysis of tree species properties

Table 1 shows the various tree species with their different properties. Properties of tree species are not independent from each other and consist of functions of physical characteristics and chemical elements. We used Pearson correlation coefficients to determine correlations among the properties of tree species. These are presented in Table 2.

Statistically significant correlations were found among heat of combustion and ash content, heat of combustion and basic density, heat of combustion and extract content and the ash content and basic density, with Pearson correlation coefficients of −0.839**, −0.661**, 0.609** and 0.826**, respectively. Heat of combustion and ash content were negatively correlated, probably caused by a suppression of the ash content by released heat, although

Table 1 Properties of tree species

tree species	heat of combustion /($\mathrm{MJ \cdot kg^{-1}}$)	fuel moisture content/%	extract content/g	ash content/g	basic density /($\mathrm{g \cdot cm^{-3}}$)	integrated attribute
Robinia pseudoacacia L.	21.508	2.364	0.123	0.120	0.923	7.71
Pinus tabulaeformis Carr.	24.271	1.309	0.152	0.027	0.854	9.04
Koelreuteria paniculata Laxm.	20.716	1.474	0.124	0.117	1.060	7.60
Syringa amurensis Rupr.	21.924	1.913	0.105	0.102	0.991	7.97
Cotinus coggygria Scop.	22.701	1.994	0.153	0.090	0.947	8.27
Amygdalus davidiana C.	23.056	1.599	0.132	0.100	1.043	8.48
Pinus armandii Franch.	24.140	1.409	0.128	0.030	0.784	8.96
Ulmus pumila L.	17.816	1.463	0.118	0.193	1.114	6.47
Platycladus orientalis Franco	23.327	1.346	0.143	0.073	0.866	8.65
Ailanthus altissima Swingle	19.719	2.348	0.122	0.123	0.982	7.03
Acer mono Maxim.	20.204	1.383	0.125	0.127	0.927	7.42
Euonymus bungeanus Maxim.	21.118	2.526	0.120	0.140	0.999	7.52
Quercus variabilis BI.	22.279	0.847	0.121	0.087	0.899	8.35
Vitex negundo var. *heterophylla* Rehd.	19.568	2.026	0.113	0.110	0.947	7.04
Sophora japonica L.	22.068	1.912	0.128	0.140	0.997	8.02
Syringa oblata Lindl.	19.683	2.651	0.101	0.113	1.002	6.94
Fraxinus chinensis Roxb.	21.375	1.270	0.103	0.087	0.915	7.91
Populus canadensis Moench.	19.601	1.489	0.100	0.170	1.070	7.15
Spiraea salicifolia L.	23.021	1.091	0.113	0.060	0.944	8.59
Armeniaca sibirica Lam.	19.732	2.019	0.098	0.117	0.943	7.10

the ash content itself did not contain heat. Heat of combustion and extract content showed a positive correlation because the extract content itself contained much heat. Basic density had a positive effect on ash content but was negatively correlated with heat of combustion. Various chemical elements can result in different basic densities and ash content as a chemical element has a higher density. Therefore, higher ash content leads to higher basic density but lower heat.

3.2 Quantitative analysis of correlated tree species properties

In order to study further the relationships between properties of tree species, prediction models in the form of simple regression equations are presented for heat of combustion as functions of ash content, extract content and basic density, obtained from regression analysis. An important relation was also found for the ash content with basic density as the independent variable.

$$H = 25.214 - 35.970A$$

$$H = 13.254 + 67.349E$$

$$H = 35.388 - 14.574\rho$$

$$A = -0.302 + 0.425\rho$$

$$H = 20.441 - 30.357A + 34.570E$$

where H is heat of combustion, A the ash content, E the extract content and ρ the basic density. The coefficient of determination (R^2) was 0.704 for heat of combustion and ash content, 0.371 for heat of combustion and extract content, 0.437 for heat of combustion and basic density, 0.683 for ash content and basic density, 0.704 and 0.785 for heat of combustion and ash content and extract content, respectively. The higher the R^2 value of the linear regression, the better the fit. The best fits were found using ash content and extract content as prediction variables for heat of combustion.

Theoretically, the main components of ash content are minerals, consisting of inorganic elements such as Na, K, Ca, Mg and Si. These elements suppress the release of heat as long as burning continues. Therefore, the lower the ash content, the more heat is produced.

The main constituents of extract content were crude fats and volatile oils, which are the most flammable parts of the chemical composition of trees. Trees with a higher extract content can produce more heat and hence become flammable. In contrast, higher concentrations of carbohydrates (e.g. cellulose and hemi-cellulose) will lead to lower heat. Additionally, the chemical compositions of most forest fuels are consistent with those of timbers, i.e., normally 40%–45% cellulose is found in timbers, 10%–15% cellulose in conifer wood, 18%–23% cellulose in broad-leafed timbers. The fact that lower amounts of

Table 2 Matrix of correlation coefficient of the properties

		FMC	ρ	H	E	A
FMC	Pearson correlation	1	0.253	−0.369	−0.183	0.354
	significance test		0.282	0.110	0.441	0.126
	number		20	20	20	20
ρ	Pearson correlation		1	-0.661^{**}	−0.351	0.826^{**}
	significance test			0.002	0.129	0
	number			20	20	20
H	Pearson correlation			1	0.609^{**}	-0.839^{**}
	significance test				0.004	0
	number				20	20
E	Pearson correlation				1	−0.419
	significance test					0.066
	number					20
A	Pearson correlation					1

** Correlation is significant at the 0.01 level (2-tailed)

cellulose are found in conifer than in broad-leaved species suggests that conifers are more flammable, which agrees with the conclusions of other researchers (Gao and Wang, 2004; Yun et al., 2005).

Variations in density mirror changes in their chemical compositions. Density varies with different tree species and in different parts of the same tree species. We found that basic density was positively correlated with ash content, which suggests that higher density decreases flammability with lower heat.

To sum up, quantitative expressions among properties are suitable and practical forms, obtained from statistical and theoretical analyses. If heat of combustion were known from investigations, then properties such as extract content, ash content and basic density could be calculated from the predictions equations, without the necessity to measure all properties of tree species.

3.3 Flammability based on properties of tree species

Direct evaluation of flammability based on a single property is complex and uncertain because of correlation among the properties of tree species. Consequently, a new integrated attribute was constructed from the original, correlated properties using principal component analysis.

$$\mathrm{IA} = -0.220\mathrm{FMC} + 0.383H + 0.290E - 0.357A$$

where IA is the integrated attribute. The correlation coefficients were −0.541 (integrated attribute and fuel moisture content), 0.941 (integrated attribute and heat of combustion), 0.713 (integrated attribute and extract content) and −0.878 (integrated attribute and ash content).

The relationship between fuel moisture content and heat of combustion was weak with a correlation coefficient of −0.369, but because fuel moisture content had little effect on the measurement of heat of combustion, flammability was studied under absolute dry conditions. Sufficient heat is needed to vaporize water before fuel can be thermally decomposed, i.e., fuel moisture slows the speed of heating in the preheating stage. Therefore, fuel moisture content is an important factor in flammability. Babrauskas (2006) took fuel moisture as a non-flammable chemical element to analyze heat of combustion of wet fuels and obtained a quantitative expression for wet fuel as a function of fuel moisture content.

$$\Delta hc(\mathrm{wet}) = \Delta hc(\mathrm{dry}) \times [100/(100 + \mathrm{MC})]$$

where Δhc(wet) is the heat of combustion of wet fuel (MJ/kg), Δhc(dry) the heat of combustion of dry fuel (MJ/kg) and MC the moisture content (%).

To summarize, the integrated attribute was negatively correlated with fuel moisture content and ash content, but positively correlated with heat of combustion and extract content. Flammable tree species have higher heat of combustion and extract content and result in higher integrated attribute values. In contrast, non-flammable tree species have higher fuel moisture and ash contents, resulting in lower integrated attribute values. We found that the integrated fuel attribute can be used to estimate the flammability of tree species.

The order of flammability from high to low was obtained from the integrated attribute as follows: *Pinus tabulaeformis* Carr. > *Pinus armandii* Franch. > *Platycladus orientalis* Franco > *Spiraea salicifolia* L. > *Amygdalus davidiana* C. > *Quercus variabilis* BI. > *Cotinus coggygria* Scop. > *Sophora japonica* L. > *Syringa amurensis* Rupr. > *Fraxinus chinensis* Roxb. > *Robinia pseudoacacia* L. > *Koelreuteria paniculata* Laxm. > *Euonymus bungeanus* Maxim. > *Acer mono* Maxim. > *Populus canadensis* Moench. > *Armeniaca sibirica* Lam. > *Vitex negundo* var. *heterophylla* Rehd. > *Ailanthus altissima* Swingle > *Syringa oblata* Lindl. > *Ulmus pumila* L. Three ranks of flammability were obtained, based on the order of flammability, by cluster analysis.

Flammable rank: *Pinus tabulaeformis* Carr., *Pinus armandii* Franch., *Platycladus orientalis* Franco, *Spiraea salicifolia* L., *Amygdalus davidiana* C., *Quercus variabilis* BI., *Cotinus coggygria* Scop.

Combustible rank: *Sophora japonica* L., *Syringa amurensis* Rupr., *Fraxinus chinensis* Roxb., *Robinia pseudoacacia* L., *Koelreuteria paniculata* Laxm., *Euonymus bungeanus* Maxim., *Acer mono* Maxim.

Non-flammable rank: *Populus canadensis* Moench., *Armeniaca sibirica* Lam., *Vitex negundo* var. *heterophylla* Rehd., *Ailanthus altissima* Swingle, *Syringa oblata* Lindl., *Ulmus pumila* L.

4 Discussion

In the first instance, properties of tree species which have a large effect on flammability, should be a part of forest combustibility evaluation. The results can probably be used as a theoretical basis for the selection of fire-resistant tree species and the establishment of fire prevention measures.

In addition, we found from our analysis that certain properties can be predicted from other known properties given their quantitative expressions. Take heat of combustion for example; it can be used to predict the extract content, ash content and basic density, without the necessity of more experiments for other properties.

Furthermore, properties of a tree species can perhaps be used to estimate its fire behavior. Take *Pinus tabulaeformis* Carr. as an example. It is ranked as flammable because of its high heat of combustion, high extract content and low ash content. Most likely, this species also releases more energy, has a high fire intensity and a faster speed of spreading, when exposed to forest fire.

Finally, it should be mentioned that the order and rank of flammability, based on our integrated attribute, suggest that *Pinus tabulaeformis* Carr., *Pinus armandii* Franch., *Platycladus orientalis* Franco are highly flammable. This fact suggests that it should be emphasized that these tree species pose a serious fire threat and should be treated for fuel reduction to prevent fire initiation and spread. In contrast, *Populus canadensis* Moench and *Ulmus pumila* L are non-flammable species and should be selected on the basis of their fire-resistance.

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