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Effects of stand composition on fire hazard in mixed-wood Canadian boreal forest

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Abstract. Surface fuels were examined in 48 stands of the Canadian mixed-wood boreal forest. Tree canopy was characterized with the point-centred quadrant method and stands were characterized as deciduous, mixed-deciduous, mixed-coniferous or coniferous according to the percentage of conifer basal area. Woody debris loadings were measured with the line intersect method and the litter, duff, shrub loads and depths or heights were sampled with various quadrats. No significant difference was found among stand types for total woody debris load, large basal diameter shrub loads and load or depth of litter and duff. However, conifer stands had significantly heavier loads of small diameter elements (twigs and shrubs) and conifer pieces were more numerous within these stands than in deciduous stands. The BEHAVE prediction system was used to evaluate the impact of these differences on the potential of fire ignition in situations where topography and weather were constant. The qualitative and quantitative changes in fuels, resulting from species replacement and fast decay rates, influence fire hazard. Simulations of fire behaviour showed that in the mixed-wood boreal forest fires were less intense and spread more slowly in deciduous stands than in mixed or coniferous stands. Moreover, spring fires were more intense than summer fires, and differences between seasons increased with the increase of deciduous basal area.

Keywords: *Abies balsamea*; BEHAVE prediction system; *Betula papyrifera*; Fire simulation; *Picea glauca*; *Populus tremuloides*; Surface fuel; *Thuja occidentalis*.

Nomenclature: Burns & Honkala (1990).

Abbreviations: BUI = Build-up Index; FWI = Fire Weather Index; HFI = Head fire intensity; ISI = Initial Spread Index; ROS = Rate of spread of fire.

Introduction

Wildfires, mainly crown fires, are one of the most important disturbances in boreal forest (Heinselman 1981; Wein & McLean 1983; Johnson 1992; Engelmark et al. 1993) shaping forest mosaics of patches, stand age and composition (Shugart et al. 1992; Bergeron & Dansereau 1993; Turner & Romme 1994). At the landscape level, the mosaic of the southeastern Canadian boreal forest is composed of deciduous, mixed and coniferous stands of different stages of post-fire secondary succession (Bergeron & Dubuc 1989; Bergeron & Dansereau 1993). Indeed, numerous studies have demonstrated, within different regions of the boreal forest, that these successional changes are examples of species dominance replacement in the canopy (Carleton & Maycock 1978; Wein & McLean 1983; Bergeron 2000). In young mixed-wood boreal forest stands, shade-intolerant species such as *Populus tremuloides* (Trembling aspen) dominate. With time, these stands develop into mixed stands as more shade-tolerant conifers eventually replace deciduous species. Stand conversion to conifers occurs gradually if the inter-fire period is sufficiently long. If the fire interval is short, shade-intolerant species will always dominate. Recent research in the southeastern Canadian boreal forest suggests that the fire return interval is being extended (Bergeron 1991; Bergeron & Archambault 1993; Flannigan et al. 1998). If so, an increasingly larger proportion of the forest will attain old-growth status with *Abies balsamea* (Balsam fir) and *Thuja occidentalis* (White cedar) as the main species (Bergeron & Dubuc 1989).

Most of the crown fires start from surface fires where surface fuels release a head fire intensity greater than the critical surface intensity needed to initiate crowning (Van Wagner 1977). This study will focus on surface fire behaviour with woody debris (i.e. twigs and branches less than 7.6 cm in diameter), litter layer, dead herbs and small basal diameter shrubs layers constituting fuels for fire ignition and surface fire propagation (Johnson 1992). Previous studies, conducted in different boreal forest regions, have demonstrated that fuel changes are responsible for different fire behaviour

(Taylor & Fonda 1989; Schimmel & Granström 1997). However, because no recent wildfires or experimental burns have been measured in the mixed-wood boreal forest, an alternative approach for assessing fire hazard and initial surface fire behaviour is to evaluate the surface fuel loads for fire hazard then input these components into a fire behaviour prediction system that models the surface fire behaviour. The BEHAVE prediction system (Burgan & Rothermel 1984; Andrews 1986; Andrews & Chase 1989) has been selected to conduct this study because it predicts surface fire behaviour from stand characteristics and the different fuel type loads collected within the stand, the Canadian Fire Behaviour Prediction (FBP) system would only require the general stand type description (Anon. 1992; Hirsch 1996).

The hypothesis is that stands of varying composition (deciduous, mixed and coniferous) have different loads and quality of surface fuels. This variability can then be related to stand fire hazard defined in the present study in terms of the characteristics (chemical and physical) of fuel elements that would favour flame propagation if ignition occurred (Montgomery & Cheo 1971). A stand with a high fire hazard possesses elements containing flammable products or products that sustain the combustion, such as low moisture and lignin contents and/or high resins or essential oil contents, (Pompe & Vines 1966; Philpot 1970; Susott et al. 1975; Susott 1980). Conifer fuel particles contain many of these products (Van Wagner 1977). Moreover, fuel elements may have a spatial distribution that can also favour fire propagation such as high surface / volume ratio, aerated particle bed or ladder fuels such as the basal conifer branches (Montgomery & Cheo 1971; Taylor & Fonda 1989). Finally, different surface fuel characteristics are hypothesized to lead to different fire behaviours (rate of spread of the fire front (m/min) and head fire intensity (kW/m) during the early phase of fire.

The objective of this study is to describe how changes in surface fuel characteristics (species composition, particle sizes, loads, spatial arrangement) during the species replacement succession in the mixed-wood boreal forest affect potential fire ignition and surface fire behaviour (mainly during the surface fire phase). We will analyse the surface fuel components (woody debris, litter, duff and shrub layers) across 48 stands that mostly differ in their canopy composition (surficial deposits, drainage, elevation, slope and natural disturbance types all being nearly identical). This will allow us to evaluate the stand fire hazard. Secondly, the initial surface fire behaviour will be modelled from these fuel types and loads for each stand using the BEHAVE prediction system.

Methods

Study area and stand selection

The study area is located around Lake Duparquet (Fig. 1), in the Clay Belt of northwestern Québec (48°30' N, 79°20' W), a large physiographic region characterized by lacustrine clay deposits left by the proglacial lakes Barlow and Ojibway (Vincent & Hardy 1977). The area surrounding Lake Duparquet has forests that have never been commercially harvested. Lake Duparquet is

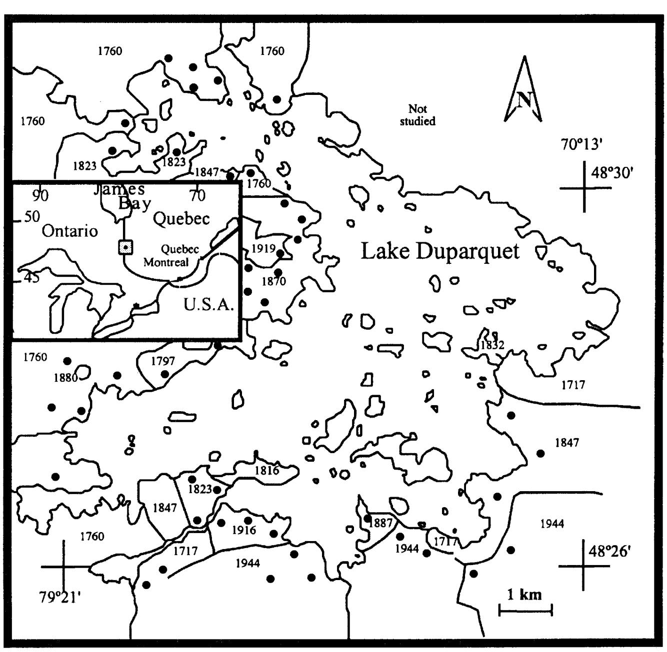

Fig. 1. Map of sampled plots around Lake Duparquet with the dates of fires occurred since 1717.

situated at the southern limit of the boreal forest in the Missinaibi-Cabonga section (Rowe 1972), in the region characterized by *Abies balsamea*, *Picea mariana* (black spruce), *P. glauca* (white spruce), *Betula papyrifera* and *Populus tremuloides* as dominating species. This region covers 123 700 km^2 in Québec (around 8% of the province, Anon. 1996) and parts of Ontario and Minnesota. Mean annual temperature is 0.6 °C; mean annual precipitation is 822.7 mm and mean annual frost-free period is 64 days. However, freezing temperatures may occur throughout the year (Anon. 1993).

48 stands were sampled on gently sloping mesic clay deposits (App. 1). All were regenerated from stand-replacing fires dating from 32 to 236 yr ago. Year of stand initiation has been determined in previous dendrochronological studies (Bergeron 1991; Dansereau & Bergeron 1993). All stands were between 4 ha and 20 ha and each was sampled with a single 30-m sided equilateral triangle (McRae et al. 1979). We sampled canopy characteristics (tree species and diameter at breast height, DBH in cm) using the point-centred quadrant method (Cottam & Curtis 1956). Six points were set up along triangle sides and 48 trees were recorded per stand: 24 dominant and 24 suppressed. The 48 distances between trees and quadrant centres were measured to calculate tree densities per stand and per species (McRae et al. 1979). Stand and species basal areas were calculated from DBH. The 48 stands were then characterized as deciduous, mixed-deciduous, mixed-coniferous or coniferous stands, if their conifer basal area was less than 25%, 25 - 50%, 51 - 75% or > 75% of the total stand basal area, respectively (App. 1). This stand type classification was chosen to reconstruct the main post-fire successional stages (Bergeron 2000).

Field sampling for the stand fire hazard evaluation

To evaluate the stand fire hazard, all surface fuel types were first measured within each stand. Woody debris was measured by the line intersect method (Van Wagner 1968, 1980) along the sides of the equilateral triangle (McRae et al. 1979). The triangular layout was used to minimize bias in situations where woody debris was not randomly oriented, and to cover the variation in woody debris distribution (Van Wagner 1980). The six Canadian diameter classes recommended by McRae et al. (1979) were used initially. Complete information, such as species coefficients and equations used for these load calculations, can be found in Hély et al. (2000) with detailed analysis of the woody debris loads and change over time since the last fire. As the BEHAVE system inputs fine woody debris from three American time lag classes (1-h, 10-h and 100-h time lags) corresponding to pieces < 0.6 cm, 0.6 - 2.5 cm and 2.7 - 7.6 cm in diameter, respectively (Bradshaw et al. 1983). A linear interpolation was used to split loads from the six Canadian classes seen above into the three American time lag classes. For example, the 100-h time lag class included 23% of the Canadian class III load (1 - 3 cm), plus the total load of classes IV and V (3 - 5 cm and 5 - 7 cm, respectively) and loads from all woody debris with diameter between 7.0 and 7.6 cm. This procedure was also used to remove woody pieces greater than 7.6 cm in diameter from the simulation as they do not take an active part in flame ignition, nor to the prediction of the fire front rate of spread. However, large woody debris can act in the flame residence time behind the fire front and information on quantity is valuable.

Shrub, herbs and litter material were measured in quadrats (Brown et al. 1982) evenly spaced along the 90-m triangle transect. Shrub basal diameters were measured by species in nine 1-m^2 quadrats at 10-m intervals and distributed into the three basal diameter size classes required by the BEHAVE system. Loads were calculated from equations determined from species shrub samples collected in the Duparquet area (Aubin 1999). Shrub height and percentage of dead shrubs were visually estimated. Herb cover was visually estimated within the nine quadrats and was relatively weighted in relation to the quadrat with the highest percentage cover (Brown et al. 1982). Material from this quadrat was then collected to evaluate its oven-dried weights. Litter and duff layer depths were measured in 12 quadrats (25 cm × 25 cm) and total litter and duff material was separately collected to obtain oven-dried weights.

The 48 loads for each surface fuel type described above were then distributed into the four stand types and were compared using a one-way non-parametric ANOVA on rank scores (Kruskal-Wallis non-parametric test) followed by Hsu's MCB multiple mean comparison test from the JUMP software (Anon. 1989) to define both quantitative and qualitative significant differences in fuel composition among the four forest stand types.

Early surface fire behaviour simulations using the BEHAVE system

Fire behaviour simulations were conducted to evaluate the effect of the different fuels within the 48 stands on the ignition potential and the fire behaviour in the first stages of the surface fire propagation using rate of spread (ROS) and head fire intensity (HFI). The burned area two hours after the fire ignition is also simulated to give the reader an idea of how the fire size increases in the early stages and how fire protection can be efficient (the larger the fire is when detected the higher the chances are for an escape from fire suppression efforts).

The BEHAVE System was developed in the USA and is composed of two subsystems: the fuel modelling subsystem referred to as FUEL (Burgan & Rothermel 1984) and the fire behaviour prediction subsystem BURN with FIRE1 and FIRE2 programs (Andrews 1986; Andrews & Chase 1989). The FUEL subsystem provides 13 standard existing fuel models that can be used unaltered or modified to create new fuel models based on measured loading data for each component. The SITE module in the FIRE1 program predicts ROS and HFI, whereas the SIZE module (also in FIRE1) calculates the area burned from a point source that results in a rough elliptical shape. The weather and topography conditions are fully described inputs in the SITE module, which uses information included in the FUEL model file to provide the fire behaviour prediction outputs. With respect to topography, a zero slope effect and an elevation of 300-m were used to represent conditions in the study area.

Because none of the 13 standard available fuel types were appropriate for the mixed-wood boreal forest, the FUEL subsystem was first used to create 48 new fuel models. Each stand structure was described with the dominant species (deciduous or coniferous), its shade tolerance, the foliage presence, the crown closure percentage (90% in deciduous, 70% in mixed-deciduous, 50% in mixed-coniferous and 30% in coniferous stands), mean tree height, the crown height/total tree height ratio and the crown height/crown diameter ratio (1 for deciduous, 1.5 for mixed-deciduous, 2 for mixed-coniferous, 2.5 for coniferous; see Andrews 1986). This stand characterization will automatically act on midflame attenuation by the wind factor and the resulting rate of spread related to this corrected wind speed. Each stand was also characterized by combinations of measured loading for the following fuel types: litter, live shrubs, 1-h time lag fuels (1-h time lag woody debris + dead shrub wood fitting in the 1-h time lag class), 10-h time lag fuels (10-h time lag woody debris + dead shrub wood fitting in the 10-h time lag class) and 100-h fuels (100-h time lag woody debris). Each fuel type was assigned a standard surface-area-to-volume ratio following the suggestions provided by Burgan & Rothermel (1984). Because spring season in the mixed-wood boreal forest is characterized without canopy and understorey cover, live shrubs (except *Taxus canadensis*) and herbs were not considered as inputs for spring fire simulations. In summer, the moisture content of living herbs and shrubs was fixed at 100% to be representative of mature foliage with completed new growth (Andrews 1986).

In order to simulate fire ignition and early fire behaviour under representative regional weather conditions, the historical 1200-h local standard time weather data (temperature, precipitation for the previous 24-h period, wind speed and relative humidity) were extracted for the 1991-1997 period from four local weather stations around Lake Duparquet and fire weather indexes (FWI) from the Canadian Forest Fire Weather Index (Van Wagner 1987) were computed for every day in these fire seasons. Three FWI values representing low, moderate and extreme fire danger conditions were selected: 5 = low; 15 = moderate; 25 = extreme; as used by SOPFEU (Society of the protection of forests against fire in Québec). Note that, over the seven year period less than 3% of days during the fire seasons had an FWI above 25. However, several days corresponded to each fire danger condition. As several combinations of intermediate FWI indices – Build-Up Index (BUI) and Initial Spread Index (ISI) – can result in the same final FWI two days per fire danger condition were selected, one with the minimum BUI and maximum ISI and the other with the maximum BUI and minimum ISI (Table 1). These six selected weather conditions for simulation (D in Table 1) and days before (D-1) were also used to evaluate the moisture content of the three time lag fuel types. The 1-h time lag fuel moisture content was calculated from the MOISTURE module of the FIRE2 BURN subsystem (Andrews & Chase 1989). The 10-h time lag fuel moisture content was predicted from the equilibrium moisture content equation of the National Fire Danger Rating System (Bradshaw et al. 1983), the previous system used in the USA. The equation calculates the 10-h time lag fuel moisture content from the 1-h time lag fuel type. Finally, the 100-h time lag fuel moisture content was directly calculated in the SITE module of the FIRE1 BURN subsystem (Andrews 1986).

Following characterization of vegetation and weather, the SITE module in the FIRE1 program was used to predict ROS in m/min and HFI in kW/m with the SIZE module, also part of the FIRE1 program, to calculate the area burned in hectares. This last fire behaviour variable

Table 1. Selected weather conditions and related fire weather indices from local meteorological stations around Lake Duparquet. Temp. = temperature (°C); Hum. = relative humidity (%); Wind = wind speed (km/h); FFMC = Fine Fuel Moisture Content; ISI = Initial Spread Index; BUI = Buildup index; FWI = Fire Weather Index; D = Weather conditions; D-1 = Weather conditions the day before the simulated day.

Repl.	Day	Temp.	Hum.	Wind	FFMC	ISI	BUI	FWI
1	D-1	30	18	21				
	D	30	24	9	87.4	4.6	11.5	5
2	D-1	19	76	6				
	D	26	53	9	72.7	1.1	76.7	5
1	D-1	14	36	3				
	D	16	35	22	89.0	11.5	15.1	15
2	D-1	28	59	5				
	D	29	65	5	86.8	3.4	92.5	15
1	D-1	22	14	7				
	D	23	14	9	95.4	14.1	40.4	25
2	D-1	31	15	4				
	D	25	29	7	91.8	8.0	85.5	25

was selected to relate the results to a potential fire attack point of view. To calculate the area burned, the elapsed time since the ignition was fixed at two hours. This elapsed time was selected to take into account the necessary acceleration time required to reach the equilibrium state previously calculated using the Canadian Forest Fire Behaviour Prediction system (Anon. 1992) from the point source ignition pattern. Without taking into account such a delay to reach the equilibrium state, ROS would have no meaning.

The experimental design for the simulations included two seasons (spring and summer (with and without understorey cover), six weather conditions (3 FWI × 2 BUI) and four stand types (each including from 4 to 24 sampled stands). This resulted in 576 simulations. For a given season and stand type, all simulations from the six weather conditions were combined. One-way non-parametric ANOVAs on rank scores and multiple mean comparison tests were used to define relative significant differences in fire behaviour components (ROS, HFI and area burned) among the four forest stand types.

Results

Fire hazard analysis

The mean stand characteristics for each surface fuel type are presented in Table 2. Total mean dead wood load per stand is 51.1 ton/ha. Woody pieces with a diameter greater than 7 cm, or the cumulative load of the three main species (*Abies balsamea*, *Populus tremuloides* and *Betula papyrifera* represent ca. 63 % of the total dead wood load. The mean duff load was 10 × heavier than the mean litter load and the duff depth was three times greater than litter depth (6.4 and 2.2 cm for duff and litter, respectively). Finally, although shrub loads were highly heterogeneous, shrub load of the 0 - 0.64 cm class was eight times lighter than the 0.64 - 2.54 cm class load and 12 times lighter than the 2.54 - 7.62 cm class load. For more details, the individual stand values are provided in App. 1.

The main successional stages known in the mixed-wood boreal forest on mesic sites can be characterized by using the percentage of living conifer basal area since this increases with mean stand age (Table 2). Deciduous stands are significantly younger than mixed and conifer stands, even though they include nine 173-yr old stands. Mixed-deciduous stands are not significantly younger than mixed-conifer stands, but they are significantly younger than conifer stands. There is also no significant difference between mixed-conifer and conifer stand ages. Concerning the different fuel types, the total dead wood load shows no significant differences among the four stand types. However, several significant differences occur once it is broken down into diameter size classes or different dead wood producing species.

Table 2. Multiple comparisons of four stand types for surface fuel characteristics.

	$p > \chi^2$	Stand type mean	Deciduous 24 stands	Mixed-deciduous 13 stands	Mixed-coniferous 4 stands	Coniferous 7 stands
Stand age	0,0001		117 ± 11 c	175 ± 15 b	205 ± 26 ab	236 ± 20 a
Dead wood						
Total load	0,5776	51.1 ± 8.1	49.5 ± 4.7	55. ± 6.4	63.8 ± 11.5	42.2 ± 8.7
Total load (0 - 0.5 cm)	0,2314	4.0 ± 0.5	3.6 ± 0.3	4.2 ± 0.4	4.6 ± 0.7	4.7 ± 0.6
Total load (0.5 - 1 cm)	0,0147	2.2 ± 0.1	1.9 ± 0.1 b	2.2 ± 0.2 b	2.5 ± 0.3 ab	3.1 ± 0.3 a
Total load (1 - 3 cm)	0,7513	5.0 ± 0.2	4.9 ± 0.3	5.0 ± 0.4	5.3 ± 0.6	5.1 ± 0.5
Total load (3 - 5 cm)	0,5008	3.5 ± 0.5	3.9 ± 0.3	3.4 ± 0.4	3.1 ± 0.7	2.8 ± 0.6
Total load (5 - 7 cm)	0,1681	4.3 ± 0.9	4.6 ± 0.6	4.4 ± 0.7	4.3 ± 1.3	3.1 ± 1.0
Total load (+ 7 cm)	0,6052	32.1 ± 8.0	30.7 ± 4.6	35.8 ± 6.3	44.0 ± 11.4	23.4 ± 8.6
Total load for *Abies balsamea*	0,0038	18.5 ± 1.8	12.7 ± 2.4 c	19.0 ± 2.9 bc	28.0 ± 5.2 ab	31.8 ± 4.0 a
Total load for *Picea glauca*	0,1762	1.5 ± 1.1	0.6 ± 0.6	2.2 ± 0.8	6.15 ± 1.5	0.4 ± 1.1
Total load for *Thuja occidentalis*	0,0006	3.0 ± 1.3	0.2 ± 1.8 b	6.2 ± 2.4 a	8.3 ± 4.3 a	4.3 ± 3.2 ab
Total load for *Populus tremuloides*	0,0001	15.0 ± 2.4	24.3 ± 2.8 a	8.4 ± 3.8 b	4.9 ± 6.9 b	0.8 ± 5.2 b
Total load for *Betula papyrifera*	0,1091	13.2 ± 6.0	11.7 ± 3.4	19.5 ± 4.7	16.6 ± 8.4	4.9 ± 6.3
Litter and duff						
Litter load	0,2388	4.4 ± 0.4	4.3 ± 0.2	4.8 ± 0.3	4.0 ± 0.5	4.5 ± 0.4
Litter depth	0,8037	2.2 ± 0.1	2.2 ± 0.1	2.3 ± 0.2	2.5 ± 0.3	2.0 ± 0.2
Litter density	0,2027	21.8 ± 1.4	22.0 ± 2.0	22.5 ± 2.8	16.0 ± 5.0	23.5 ± 3.8
Duff load	0,2813	46.7 ± 5.4	44.3 ± 3.1	48.4 ± 4.2	54.4 ± 7.7	47.7 ± 5.8
Duff depth	0,1761	6.4 ± 0.3	5.9 ± 0.3	6.8 ± 0.5	7.4 ± 0.9	6.6 ± 0.6
Duff density	0,9633	73.5 ± 2.7	74.3 ± 4.0	73.1 ± 5.4	73.9 ± 9.7	71.1 ± 7.3
Shrubs						
Total load in class (0 - 0.64 cm)	0,0167	0.2 ± 0.0	0.1 ± 0.0 b	0.2 ± 0.0 ab	0.2 ± 0.0 ab	0.4 ± 0.1 a
Total load in class (0.64 - 2.54 cm)	0,0036	1.7 ± 0.2	1.0 ± 0.3 b	2.3 ± 0.4 a	1.9 ± 0.7 ab	2.8 ± 0.5 a
Total load in class (2.54 - 7.62 cm)	0,2053	2.5 ± 1.8	1.6 ± 1.0	2.6 ± 1.3	1.1 ± 2.4	4.5± 1.8

Note: *p*-results from Kruskal-Wallis' test. Loads are in t/ha, depths in cm, and densities in kg/m^3. Values are means ± standard error. Values in a row followed by the same letter are not significantly different at $\alpha = 0.05$ for Hsu's test.

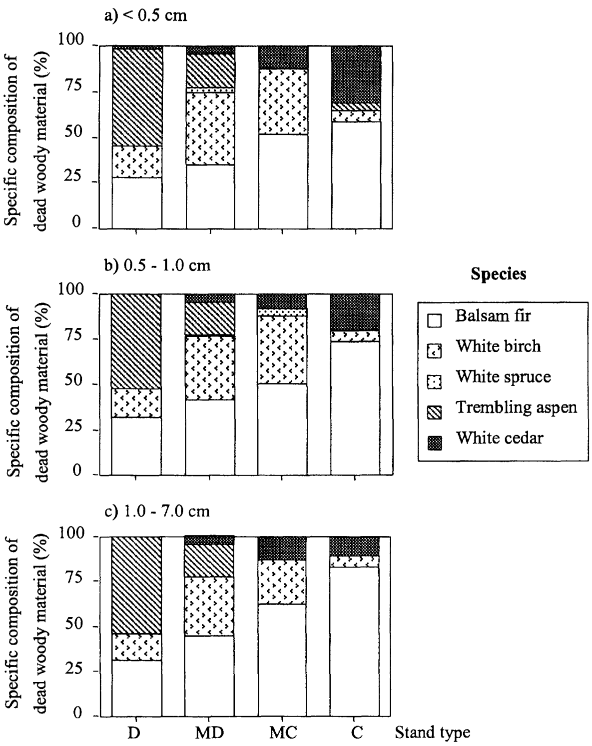

Fig. 2. Mean specific composition (%) of dead woody pieces within each stand type. D = deciduous; MD = mixed-deciduous; MC = mixed-coniferous; C = coniferous, for three diameter size classes.

Loads of the 0.5-1 cm diameter class, as well as the woody debris loads of *Abies balsamea* and *Thuja occidentalis*, significantly increase with the increase of conifer basal area, whereas the *Populus tremuloides* dead wood load significantly decreases. There were no

Table 3. Results of Kruskal-Wallis and multiple comparison tests on rank scores for simulated ROS, HFI and area burned for spring and summer seasons using the BEHAVE system. D = deciduous; MD = mixed-deciduous; MC = mixed-coniferous; C = coniferous. Score means from the Kruskal-Wallis tests are given for each combination for a given season; results with the same letters are not significantly different at $\alpha = 0.05$ from the Hsu's MCB tests.

Season	Stand type	Rate of spread Score mean	Head fire intensity Score mean	Area burned 2h since ignition Score mean
Spring	χ^2	12.723	47.860	18.629
	p	0.0053	0.0001	0.0003
	D	130.87 b	114.837 c	126.219 b
	MD	161.04 a	169.154 ab	165.538 a
	MC	134.10 ab	135.708 bc	130.604 ab
	C	166.45 ab	205.440 a	176.048 ab
Summer	χ^2	20.216	68.253	33.212
	p	0.0002	0.0001	0.0001
	D	127.545 b	109.483 c	119.580 b
	MD	152.737 a	162.615 b	158.333 ab
	MC	151.104 ab	155.917 b	154.208 a
	C	183.560 a	224.393 a	198.702 a

significant differences among the four stand types for the *Picea glauca* and *Betula papyrifera* loads or for any other size class loads. These changes in species composition of dead woody material among different stand types are illustrated in Fig. 2 in terms of species percentages across diameter size classes. It is interesting to note that litter and duff components present no difference in relation to the change of stand composition (Table 2). Finally, the two first shrub load classes (less than 2.5 cm in diameter) are significantly lower in the pure deciduous stands.

Table 4. Surface fuel components characteristics for comparisons with other boreal forests.

Stand type	Basal area of living trees (m^2/ha)	Stand age (yr)	Total log volume (m^3/ha)	Duff load (t/ha)	Duff depth (cm)	References
Deciduous	45.9 ± 3.8	117 ± 11	40.1 ± 3.8	44.3 ± 3.1	5.9 ± 0.3	this study
Deciduous		88 - 108	16 - 80©			1
Deciduous (*Populus tremuloides*)		23 - 146	108.8 - 124.3			2
Deciduous (*Populus tremuloides*)			38.3 - 60.0 @			3
Deciduous (*Betula papyrifera*)			24.8 - 68.8 @			3
Deciduous	29,3		13.0 - 19.9 #			4
Mixed (deciduous >)	37.4 ± 5.2	175 ± 15	44.6 ± 5.2	48.4 ± 4.2	6.8 ± 0.5	this study
Mixed (coniferous >)	26.1 ± 9.4	205 ± 26	51.7 ± 9.4	54.4 ± 7.7	7.4 ± 0.9	this study
Mixed	28.0 - 33.1		32.7 #			4
Mixed (coniferous >)	22.1 ± 50.5	33 -110	15 - 80			5
Coniferous	35.3 ± 7.1	236 ± 20	34.2 ± 7.1	47.7 ± 5.8	6.6 ± 0.6	this study
Coniferous (spruce)		133 - 245	34 - 166©			1
Coniferous (pines)		117 - 270	31 - 68©			1
Coniferous (fir)				65 - 117 @		3
Coniferous (spruce)				63.7 - 128.9 @		3
Coniferous	25.4 - 30.5		41.6 - 56.5 #			4
Coniferous (spruce-fir)		51 - 55		17	6.6 - 7.9	6

= only logs greater than 5 cm in diameter; ©= only logs greater than 10 cm in diameter ; @ = litter and duff included; references: 1 = Linder et al. (1997); 2 = Lee et al. (1997); 3 = Vogt et al. (1986); 4 = Freedman et al. (1996); 5 = Sturtevant et al. (1997); 6 = Barney & Van Cleve (1973).

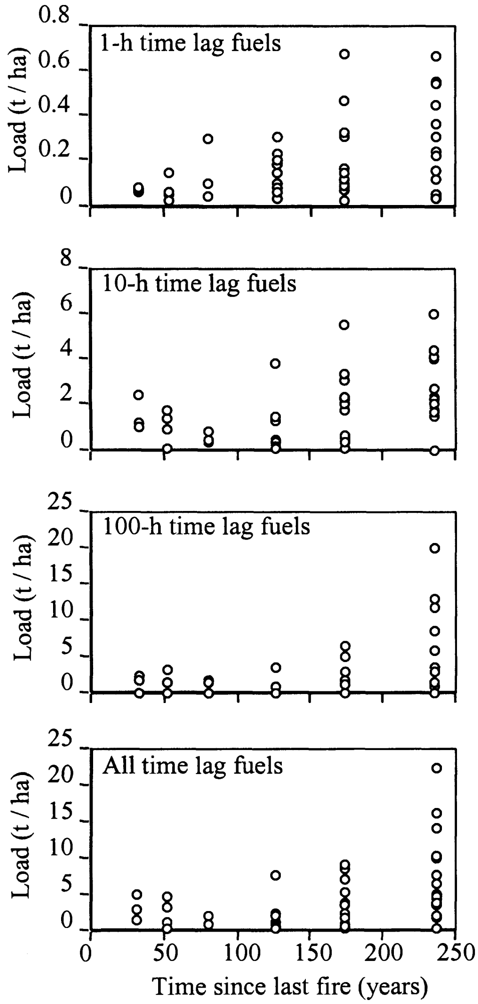

Fig. 3. Changes within the different time lag fuel loads through time since the last fire.

Potential fire behaviour among the four stand types

The fire behaviour predictions (score means) from the BEHAVE System for spring and summer and the results of the comparisons among the four stand types are reported in Table 3. The six tests are all significant. For deciduous and mixed-deciduous stand types, score means tend to be higher in spring than in summer, whereas mixed-coniferous and coniferous stands score means are higher in summer than in spring. For all fire behaviour variables, and throughout the fire season, deciduous stands yield the lowest significant predicted values, while coniferous stands show the highest relative values for the same variables. Mixed stands always have intermediate predicted values, with no significant differences between mixed-deciduous and mixed-coniferous stands.

Discussion

Linder et al. (1997) observed fuel loads that ranged from 16 to 80 m^3/ha for deciduous stands and from 31 to 168 m^3/ha for coniferous stands. For the mixed-coniferous stands Sturtevant et al. (1997) found values that ranged from 15 to 80 m^3/ha. Noticeable differences in log volumes were found by Lee et al. (1997) for deciduous stands (109 - 124 m^3/ha) in Alberta and by Freedman et al. (1996) for deciduous and mixed stands (13 - 20 and 33 m^3/ha, respectively) in New Brunswick. It is likely that the drier climate in Alberta creates a less favourable environment for decomposing fungi. This would slow down bole decay rate and result in greater log accumulation. Conversely, in New Brunswick, the moister climate has the opposite effect and favours log decay. Moreover, Freedman et al. (1996), by sampling only logs > 5 cm in diameter, have not taken into account small diameter log loads that can comprise up to 43% of the total load in our study area. In boreal forest studies dealing with organic matter characteristics, data for duff are more numerous than those for litter. Even though the fuelbeds have variable composition, total loads from this study were in the same value ranges as those observed in other studies (Vogt et al. 1986; Barney & Van Cleve 1973).

The southeastern Canadian mixed-wood boreal forest appears as a relative homogeneous forest mosaic at the landscape level when total amounts of surface fuels are analysed. When the four different stand types are used as successive stages to reconstruct the post-fire succession pathway (Bergeron 2000) homogeneity still exists (Table 2), but it is explained by the high variability of species replacement rates. For example, nine sampled stands over 150 yr old are still dominated by deciduous species, mainly *Populus tremuloides*. If the different time lag fuel loads are plotted against time since the last fire (Fig. 3), there is a non-significant increase of loads with time for all time lag classes, which partially confirms accumulation patterns of fuels through time found in previous studies in the boreal forest (Wein & McLean 1983; Lee et al. 1997; Sturtevant et al. 1997). However the mixed-wood boreal forest data do not present the common U-shape pattern (Hély et al. 2000) found in other boreal forest types (Lambert et al. 1980; Lee et al. 1997; Sturtevant et al. 1997). Low accumulation in the mixed-wood boreal forest is the result of species replacement in the canopy through time, the rate of changes (App. 1 and Bergeron & Dubuc 1989) and fast decay rates observed for the involved species (Alban & Pastor 1993) and their different elements (wood, leaves and needles).

However, composition and quality of dead wood fuels do change considerably from deciduous towards coniferous elements (Fig. 2, Table 2, and App. 2), and this replacement is correlated to the basal areas of the dominating trees of the canopy (Hély et al. 2000). This change in fuel elements will lead to a simultaneous increase in the amount of conifer pieces, which are more flammable than deciduous pieces (Brown & Davis 1973; Rowe & Scotter 1973) and an increase in small dead wood loads. These changes are likely to increase the stand fire hazard. Moreover, with time since the last fire, the associated development of basal conifer branches that can act as vertical fuel ladders for fire propagation from surface to crown layers will also increase (Heinselman 1973). This illustrates qualitative change in fuel spatial arrangement that really exists and acts in fire propagation but which is not taken into account in the BEHAVE system.

For the litter and duff layers, Paré et al. (1993) found similar results for the litter layer with no difference in load along the chronosequence, whereas they found a significant increase in the ash-free dry weight of the duff layer with time (not significant in the present study, see Table 2). However, the fire hazard of the litter compartment should change from deciduous to coniferous stands. As the structure of the litter changes from deciduous leaves to needles, litter should decrease the compactness of the litter bed and create a more aerated fuelbed that could more easily propagate the flame and lead it to reach shrubs and ladder fuels.

The increase of the small diameter shrub loads from deciduous to coniferous stands is the result of a change in shrub composition with the canopy species replacement (De Grandpré et al. 1993). *Taxus canadensis* is a low evergreen shrub with small diameter stems that dominates the shrub layer in the mixed-conifer and coniferous stands, whereas the deciduous and mixed-deciduous stands are frequently dominated by herb species such as *Aster macrophyllus* and *Aralia nudicaulis* or tall shrubs with large diameter stems such as *Acer spicatum* and *Corylus cornuta* (De Grandpré et al. 1993). These changes in the shrub layer from deciduous to coniferous dominated stands are also expected to increase the fire hazard as the load of small diameter fuels increases and this is further enhanced as *Taxus canadensis* contains flammable essential oils.

The increase in fire hazard along the tree species replacement in the canopy was partially confirmed by comparisons of simulations from the BEHAVE System. Deciduous stands, when they do burn, sustain fire behaviour with relatively low intensity and ROS (score means) compared to conifer stands that can sustain relatively high fire intensity and ROS. These differences in fire behaviour imply relatively smaller burn areas in deciduous stands than in conifer stands for a given period of time. However, the predicted values of fire intensity, rate of spread and area burned from BEHAVE should be used with caution because no comparison can be conducted with real fire behaviour data recorded in the mixed-wood boreal forest. Indeed, there is a lack of data from wildfires or prescribed burns that would have occurred in this forest ecosystem type (Hirsch 1996). To develop the FBP system that is used across Canada, the Canadian Forest Service had to create mixed-wood boreal forest equations for fire behaviour components from data available recorded for *Picea mariana* and *Populus tremuloides* stands (Anon. 1992; Hirsch 1996). This system predicts fire behaviour from the FWI and the canopy composition in terms of percentage of conifer for the mixed-wood stand types. Some simulation tests with FBP would show higher predicted values than those predicted by BEHAVE. Nevertheless, using the FBP system, deciduous stands would always record the less intense fire behaviour, mixed stands would present moderate fire intensities, while conifer stands would record the most extreme fire behaviour.

Season is also an influencing factor on fire hazard because spring simulations yielded higher values of fire behaviour variables than those observed in summer. The higher the deciduous percentage, the higher spring and summer differences; however, the only difference recorded between spring and summer is exclusive to vegetation phenology with the presence or absence of deciduous leaves. In spring, the total absence of deciduous foliage does not interfere with the direct ground and surface fuel bed warming from direct sunlight (Furyaev et al. 1983) whereas in summer deciduous leaves intercept the sunlight and create a cool and moist understorey and ground environments (Van Wagner 1983). The BEHAVE system takes this seasonal change into account with the date, the main species (deciduous or conifer) and the foliage presence requirements. It results in a slower ROS for deciduous dominated stands in summer, associated with less intensity released and smaller burned areas, than in spring. Conifer stands in this region are generally older, and they present a more open canopy than deciduous stands. Because these conifer species are evergreen, new foliage represents only a small proportion of their total foliage load (Brown & Davis 1973). The difference of environment within a conifer canopy between spring and summer will be small, and differences in fire behaviour will come from herb cover presence in summer that has a higher moisture content in the surface fuels and decreases the propagation rate. However, these smaller values in fire behaviour components for summer simulations are not visible for conifer dominated stands in Table 3 as only the relative differences between stands are reported. In this case, the differences between deciduous and coniferous dominated stands overwhelm the seasonal effect within a given stand.

Conclusion

Analysis of the different surface fuel types in the mixed-wood boreal forest suggests that stand fire hazard increases through canopy tree species replacement sequence in the southeastern Canadian boreal forest. This increase in fire hazard does not result from a heavy fuel load accumulation but rather from changes in the quality of surface fuels. Flammable materials (small woody particles, conifer pieces, aerated organic matter bed) are more important in mixed or coniferous stands than deciduous ones. The modelling aspect of fire behaviour suggests an increase in fire rate of spread and head fire intensity with increasing conifer density in late successional stands.

Fuel load accumulation through time exists in the mixed-wood boreal forests, but it is less important to fire behaviour than in other forest ecosystems. Nevertheless, the fire suppression policy exerted in the region and the global warming trend – including a decreasing fire frequency – will contribute to an ageing of the forest mosaic. Therefore, the coniferous stand proportion has a chance to increase. The stand fire hazard will then increase not from a long-term heavy fuel accumulation but from a more flammable and susceptible fuel composition.

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App. 1. Stand and surface fuel characteristics of the 48 sampled stands.

Stand no.	Total live tree basal area (m^2/ha)	Percent conifer basal area	Total live tree density (stems/ha)	Time since last fire (yr)	Total dead wood load (t/ha)	L. depth (cm)	L. load (kg/m^2)	L. bulk density (kg/m^3)	D. bulk density (kg/m^3)	1-h time lag (t/ha)	10-h time lag (t/ha)	100-h time lag (t/ha)
p0301	51.27	0	2382	32	27.7	0.62	0.429	69.6	152.3	0.06	1.18	0.00
p0302	42.80	0	1978	32	22.6	1.33	0.451	33.8	33.7	0.07	2.40	2.30
p0303	35.33	0	1234	32	26.2	1.46	0.435	29.8	81.0	0.08	0.99	1.75
b0552	18.98	4	1478	52	43.6	1.92	0.235	12.2	61.1	0.05	1.35	3.17
p0552	37.53	4	1901	52	27.0	2.90	0.467	16.1	77.2	0.06	0.93	0.00
p1706	47.09	4	1111	173	41.2	2.13	0.435	20.5	62.3	0.15	1.79	1.31
p1707	31.66	5	748	173	46.6	2.33	0.387	16.6	68.8	0.02	0.03	0.00
p0551	22.43	7	1055	52	27.6	1.46	0.336	23.0	96.6	0.04	0.83	0.00
p0801	125.57	7	3422	80	89.2	2.25	0.440	19.6	65.0	0.04	0.38	1.57
p1710	50.90	7	1045	173	39.6	3.08	0.539	17.5	54.3	0.30	0.32	0.00
p0802	60.49	8	2823	80	17.8	2.07	0.413	20.0	67.2	0.10	0.44	1.46
p1201	47.73	8	1205	126	29.8	1.83	0.491	26.8	94.3	0.10	0.39	0.70
p1205	70.96	9	712	126	65.4	2.63	0.357	13.6	77.0	0.19	0.07	0.00
p1704	64.38	15	825	173	61.0	2.58	0.304	11.8	71.5	0.23	1.29	0.64
p1705	39.50	16	1800	173	82.6	2.38	0.333	14.0	93.2	0.31	1.48	0.00
p1709	57.41	18	1430	173	57.0	2.75	0.552	20.1	65.0	0.15	0.03	0.00
b1201	31.81	19	1702	126	51.1	2.92	0.372	12.8	68.6	0.03	0.32	0.00
b1203	21.20	19	2168	126	51.9	2.46	0.445	18.1	85.4	0.08	3.88	3.56
p1203	44.08	19	753	126	64.9	1.96	0.539	27.5	67.7	0.20	0.10	0.00
p1204	54.67	22	632	126	31.4	1.63	0.491	30.2	61.6	0.06	0.03	0.00
b1702	22.83	22	878	173	67.9	2.13	0.547	25.7	72.4	0.31	0.39	0.00
p1702	26.69	22	1646	173	68.1	2.71	0.413	15.3	89.8	0.33	5.56	0.96
b0801	64.94	23	2309	80	111.5	3.08	0.469	15.2	66.6	0.08	0.57	0.00
p1703	32.36	23	861	173	36.1	2.42	0.419	17.3	51.2	0.02	0.02	0.00
b1202	25.91	26	1581	126	26.0	1.75	0.557	31.8	52.9	0.07	0.59	0.00
b0802	45.06	28	1139	80	70.0	2.75	0.507	18.4	78.2	0.17	1.76	1.68
p1202	35.81	29	1265	126	24.1	2.00	0.523	26.1	124.9	0.10	2.26	0.00
b0551	39.41	30	1072	52	35.4	1.25	0.523	41.8	77.8	0.09	0.66	0.92
p2103	68.88	30	1002	236	46.4	2.38	0.611	25.7	77.8	0.68	3.05	4.77
p1701	31.40	32	1160	173	56.8	2.08	0.387	18.6	83.6	0.12	2.08	2.89
p1708	32.14	32	627	173	42.4	3.13	0.544	17.4	63.2	0.17	0.34	0.00
b2102	37.74	35	673	236	54.9	2.38	0.411	17.3	68.1	0.47	2.32	6.36
b2101	30.44	41	444	236	70.5	3.00	0.573	19.1	74.2	0.15	3.36	0.00
b2104	24.06	41	1084	236	108.3	2.29	0.139	6.1	59.4	0.16	1.47	0.00
p2102	37.15	44	570	236	41.1	1.90	0.517	27.2	52.5	0.04	2.33	11.78
p2101	52.66	46	906	236	44.5	2.71	0.491	18.1	60.3	0.31	6.00	0.00
b1204	25.80	48	1057	126	95.6	1.83	0.453	24.7	77.4	0.24	4.11	5.70
b2103	22.98	51	775	236	103.4	2.04	0.187	9.1	73.7	0.05	1.43	3.48
b1701	15.50	64	1065	173	69.8	2.90	0.408	14.1	72.7	0.31	2.27	0.79
t2101	36.33	66	820	236	47.2	3.13	0.531	17.0	76.0	0.37	4.01	0.00
b1703	29.57	71	1650	173	35.6	2.00	0.475	23.7	73.0	0.03	0.00	0.00
t2102	68.12	78	578	236	42.0	2.08	0.472	22.7	68.7	0.22	1.46	8.43
s2101	23.30	79	999	236	46.9	2.92	0.533	18.3	51.5	0.56	4.13	0.00
s2102	26.30	82	961	236	34.9	0.75	0.237	31.6	58.6	0.16	1.73	0.00
t2105	43.58	89	437	236	26.8	1.75	0.424	24.2	75.0	0.67	1.64	1.40
t2106	37.33	90	1136	236	52.2	2.08	0.627	30.1	91.2	0.12	2.07	20.16
t2104	33.03	93	1288	236	48.0	2.38	0.451	19.0	80.0	0.55	2.73	12.88
t2103	15.10	100	1086	236	44.7	2.13	0.400	18.8	72.3	0.45	4.41	2.76

Note: only stems greater than 5 cm in DBH were measured. L. = litter; D. = duff.

App. 2. Species composition (%) of dead wood material < 7 cm in diameter. Pt = *Populus tremuloides*; Bp = *Betula papyrifera*; Pg = *Picea glauca*; To = *Thuja occidentalis*; Ab = *Abies balsamea.*

Stand no.	Percent conifer basal area	Time since fire (yr)	Percent of species composition of dead wood material by diametersize class Class I (0 - 0.5 cm)					Class II (0.5 - 1 cm)					Classes III, IV, and V (1 - 7 cm)				
			Pt	Bp	Pg	To	Ab	Pt	Bp	Pg	To	Ab	Pt	Bp	Pg	To	Ab
p0301	0	32	100	0	0	0	0	100	0	0	0	0	100	0	0	0	0
p0302	0	32	80	20	0	0	0	77	23	0	0	0	77	23	0	0	0
p0303	0	32	100	0	0	0	0	100	0	0	0	0	100	0	0	0	0
b0552	4	52	0	100	0	0	0	10	90	0	0	0	0	100	0	0	0
p0552	4	52	100	0	0	0	0	93	7	0	0	0	100	0	0	0	0
p1706	4	173	70	0	0	0	30	57	0	0	0	43	57	0	0	0	43
p1707	5	173	43	0	0	7	50	23	0	0	0	77	23	0	0	0	77
p0551	7	52	80	20	0	0	0	80	20	0	0	0	80	20	0	0	0
p0801	7	80	87	10	0	0	3	87	10	0	0	3	87	10	0	0	3
p1710	7	173	67	0	0	0	33	47	0	0	0	53	60	0	0	0	40
p0802	8	80	80	0	0	0	20	80	0	0	0	20	80	0	0	0	20
p1201	8	126	70	0	0	0	30	70	0	0	0	30	60	0	0	0	40
p1205	9	126	67	3	0	20	10	70	0	0	0	30	63	3	0	3	30
p1704	15	173	70	0	0	0	30	43	0	0	0	57	47	0	0	0	53
p1705	16	173	70	0	0	0	30	60	0	0	0	40	67	0	0	0	33
p1709	18	173	23	17	0	0	60	33	0	0	0	67	33	7	0	0	60
b1201	19	126	0	37	0	0	63	0	37	0	0	63	0	37	0	0	63
b1203	19	126	0	67	0	0	33	0	67	0	0	33	0	57	0	0	43
p1203	19	126	50	0	0	0	50	50	0	0	0	50	50	0	0	0	50
p1204	22	126	50	33	0	0	17	83	0	0	0	17	83	0	0	0	17
b1702	22	173	0	53	0	0	47	0	40	0	0	60	0	43	0	0	57
p1702	22	173	47	0	0	0	53	40	0	0	0	60	50	0	0	0	50
b0801	23	80	0	67	0	0	33	0	77	0	0	23	27	50	0	0	23
p1703	23	173	20	0	0	0	80	47	0	0	0	53	47	0	0	0	53
b1202	26	126	0	53	0	0	47	0	53	0	0	47	0	60	0	0	40
b0802	28	80	7	73	0	0	20	7	73	0	0	20	10	67	0	0	23
p1202	29	126	53	17	0	0	30	53	17	0	0	30	53	17	0	0	30
b0551	30	52	0	93	0	0	7	0	63	0	0	37	0	63	0	0	37
p0801	7	80	87	10	0	0	3	87	10	0	0	3	87	10	0	0	3
p1710	7	173	67	0	0	0	33	47	0	0	0	53	60	0	0	0	40
p0802	8	80	80	0	0	0	20	80	0	0	0	20	80	0	0	0	20
p1201	8	126	70	0	0	0	30	70	0	0	0	30	60	0	0	0	40
p1205	9	126	67	3	0	20	10	70	0	0	0	30	63	3	0	3	30
p1704	15	173	70	0	0	0	30	43	0	0	0	57	47	0	0	0	53
p1705	16	173	70	0	0	0	30	60	0	0	0	40	67	0	0	0	33
p1709	18	173	23	17	0	0	60	33	0	0	0	67	33	7	0	0	60
b1201	19	126	0	37	0	0	63	0	37	0	0	63	0	37	0	0	63
b1203	19	126	0	67	0	0	33	0	67	0	0	33	0	57	0	0	43
p1203	19	126	50	0	0	0	50	50	0	0	0	50	50	0	0	0	50
p1204	22	126	50	33	0	0	17	83	0	0	0	17	83	0	0	0	17
b1702	22	173	0	53	0	0	47	0	40	0	0	60	0	43	0	0	57
p1702	22	173	47	0	0	0	53	40	0	0	0	60	50	0	0	0	50
b0801	23	80	0	67	0	0	33	0	77	0	0	23	27	50	0	0	23
p2103	30	236	13	3	0	20	63	12	3	0	8	77	15	10	0	12	63
p1701	32	173	67	0	0	0	33	63	0	0	0	37	57	0	0	0	43
p1708	32	173	63	0	0	0	37	57	0	7	0	37	40	0	0	0	60
b2102	35	236	0	23	23	10	43	0	27	0	33	40	0	33	0	23	43
b2101	41	236	0	90	0	0	10	0	60	0	0	40	0	43	0	0	57
b2104	41	236	0	70	0	13	17	0	43	0	0	57	0	60	0	0	40
p2102	44	236	7	60	10	0	23	13	67	7	0	13	23	17	13	0	47
p2101	46	236	33	0	0	0	67	33	0	0	7	60	37	0	0	10	53
b1204	48	126	0	37	0	7	57	0	40	0	3	57	0	60	0	0	40
b2103	51	236	0	37	0	0	63	0	50	0	0	50	0	10	0	0	90
b1701	64	173	0	43	0	0	57	0	47	0	0	53	0	47	0	0	53
t2101	66	236	0	37	0	47	17	0	27	17	30	27	0	3	0	50	47
b1703	71	173	3	27	0	0	70	0	27	0	0	73	0	40	0	0	60
t2102	78	236	7	0	0	57	37	3	0	0	47	50	3	10	0	33	53
s2101	79	236	20	3	0	0	77	3	0	0	0	97	0	0	0	0	100
s2102	82	236	0	8	0	18	73	0	17	0	27	57	0	0	0	3	97
t2105	89	236	0	0	0	87	13	0	3	0	10	87	0	13	0	0	87
t2106	90	236	0	7	0	13	80	0	2	0	15	83	0	0	0	3	97
t2104	93	236	0	3	0	30	67	0	7	0	23	70	0	17	0	17	67
t2103	100	236	0	23	0	10	67	0	10	0	13	77	0	0	0	17	83

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