
BIOMASS CONSUMPTION AND SMOKE EMISSIONS FROM CONTEMPORARY AND PREHISTORIC WILDLAND FIRES IN BRITISH COLUMBIA

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Biomass Consumption and Smoke Emissions from Contemporary and Prehistoric Wildland Fires in British Columbia

by

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EXECUTIVE SUMMARY

Wild and prescribed fires affect extensive areas of forest land in British Columbia. Wildfires occur both naturally and as a result of human activity. Prescribed fire is a widely used practise in resource management, and includes broadcast and spot burning of logging slash for site preparation and wildfire hazard reduction, and burning of natural areas for wildlife habitat and range enhancement. While there has been recurring concern about the potential effects of smoke from wildland fires on air quality, the quantity of smoke emissions has not been well established. Furthermore, smoke production from the presettlement fire regime was not considered previous to this report.

The objectives of this study were to develop smoke emission inventory procedures for B.C. and to provide benchmark estimates of biomass consumption and smoke emission yields from wild and prescribed fires in British Columbia forests in contemporary and prehistoric times. A 10-year period (1981-90) was examined in order to encompass some of the annual variation in the wildfire activity that is due to climate.

The average annual biomass consumption in wildland fires during 1981-90 was 12.4 million tonnes. During this period, emissions of PM_{2.5}, PM₁₀, TSP, CO, CH₄, NO_x, and N₂O were 141, 152, 200, 1283, 72, 17, and 4 kilotonnes, respectively; CO₂ emissions were about 20.6 million tonnes. Broadcast burns, spot burns, wildlife/range burns, and wildfires accounted for 27, 11, 17, and 45% of total emissions, respectively. However, there was substantial variation in emission production between years (125, 40, and 48% for wildfires, prescribed fires, and all wildland fires, respectively) during this period. Prescribed fire emissions exceeded those for wildfire in 6 of the 10 years.

The seasonal distribution of wildland fire activity in B.C. was examined for 1990 and 1991. Wildland fires occurred mainly between May and November; effects of wildland fires on air quality were probably episodic, rather than continuous. The relative contribution of wild and prescribed fire sources to emission production varied during these years: the largest smoke source in May was wildlife/range burns, while wildfires dominated in July and August, broadcast burns in September, and spot burns in October and November.

Smoke emission production from prehistoric wildland fires was estimated to be 3-6 times larger than the average annual contemporary production. This is mainly attributed to greater wildfire activity.

The effects of smoke emissions on air quality are strongly affected by atmospheric conditions, topography, and the proximity of the smoke source to the receptor. More-detailed models that incorporate these factors are needed to assess the effect of wildland-fire smoke on air quality. Recommendations for improving future inventories are also given.

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1 INTRODUCTION

Incomplete combustion of forest biomass results in the release of water vapour, carbon dioxide, particulate matter, carbon monoxide, methane, and other trace gases to the atmosphere. The amount of emissions produced by a particular fire depends on the quantity of biomass consumed and on combustion efficiency.

Every year in British Columbia, a substantial amount of smoke is produced by the combustion of forest biomass. Forest biomass is consumed in wild and prescribed fires, in industrial woodwaste burning, in land clearing, and in residential burning. There have been recurring concerns about the effects on visibility and health of smoke from biomass fires in B.C. (Nikleva 1972; B.C. Environment 1991; Vedal 1993, 1995), but emissions production has not been well documented.

Recent greenhouse gas inventories for British Columbia (Levelton and Assoc. 1990, 1991; Concord Environmental Corp. 1992) and Canada (Jaques 1992) included estimates of CO₂, CH₄ and N₂O/NO_x from wildland fires. However, Lawson and Taylor (1990) argued that with respect to CO₂, much of the gas released during prescribed fires in British Columbia would otherwise be released by biological decomposition over a longer period of time, and that emissions from burning of forest biomass should be viewed within the context of the complete forest carbon cycle. Jaques (1992) also suggested that emissions from biologically derived sources should not be included in greenhouse gas inventories because carbon sinks (vegetation and soil) are directly related to the size of the sources (fire and decomposition), assuming that sustainable practices are used. Recent analyses of the carbon budget of the Canadian forest sector suggest that forests were a net sink of atmospheric carbon in Canada during 1986, and in British Columbia during 1920–90 (Kurz *et al.* 1992, 1996).

The objectives of this study were to develop estimates of smoke emissions from wild and

prescribed fires in B.C. forests during 1981–90, and to compare these with amounts that occurred before European settlement. The prescribed fires included in this study were carried out under burning permits issued under the Forest Act (British Columbia). The objectives of the fire treatments included site preparation, wildfire hazard reduction, and wildlife habitat/range enhancement (the treated areas remain as forest land). The methods used were broadcast burning and burning of piled and windrowed debris. The burns took place on logging sites and landings, and in natural forest and grassland areas.

Emissions estimates are needed to help guide the development of smoke management programs, policies, and research, and to provide a benchmark to evaluate the effect of smoke management practises. A multi-year period was examined because there is significant annual variation in the area burned by wildfire or treated by prescribed fire, and consequently in emissions production.

Eight smoke constituents are included in the inventory: total suspended particulates (TSP), <10 µm particulates (PM₁₀), <2.5 µm particulates (PM_{2.5}), CO₂, CO, CH₄, N₂O and NO_x. Particulates were included because of their potential effects on visibility and health (the fine particulate fraction (PM_{2.5}) has the most significant effects on health and visibility). The trace gases were included to provide better data for carbon budget and atmospheric modelling. Earlier CO₂, CH₄, and N₂O/NO_x inventories in British Columbia (Levelton and Assoc. 1990, 1991; Concord Environmental Corp. 1992) and Canada (Jaques 1992) did not include all types of fire, and were for single and different reference years. However, it is not to be inferred that these trace gases contribute directly to British Columbia's greenhouse gas budget.

2 DATA SOURCES AND METHODS

The yield of individual smoke constituents from wildland fires can be estimated as the product of fuel consumption, emission factors, and the area burned (Yanate 1971 cited in Ward *et al.* 1993):

$$\text{Yield (t)} = \text{Biomass consumption (t/ha)} \times \text{Emission factor (g/kg)} \times \text{Area burned (ha)/1000}$$

In this study, emission yields from aggregated estimates of annual fire activity and biomass consumption during 1981–1990 were calculated because individual fire data were not available for all types of fires.

2.1 Fuel Consumption in Wildland Fires

The biomass consumed in wildland fires may include forest floor organic matter (LFH), understory vegetation, standing and downed woody debris, tree foliage, branches, bark, and stemwood. There is substantial variation in the amount of biomass consumed between fires, depending mainly on how much is present and on its distribution and moisture content. In forested areas, the amount of biomass present varies with tree species composition, stand age, density, site productivity, and disturbance history. The amount of biomass remaining after logging depends on the quality of the stand and on logging methods. Subsequent treatments such as piling can further alter the distribution of debris.

However, because biomass consumption is not routinely measured or estimated for individual wildland fires in B.C., typical values for different types of fire and ecosystems were used. The biogeoclimatic zones of B.C. (Meidinger and Pojar 1991), were used to represent broad ecosystem types. The types of fire examined were wildfires, broadcast, spot (windrowed and piled debris), landing, and wildlife habitat/range improvement burns. Biomass consumption estimates were compiled for each fire type by biogeoclimatic zone and year,

based on estimates of typical biomass consumption per unit area by fire type and zone, and on estimates of the corresponding area burned by fire type, zone, and year. Estimates for the Sub-Boreal Spruce and Sub-Boreal Pine-Spruce zones and the Ponderosa Pine and Bunchgrass zones were combined in order to be compatible with an earlier version of the ecological classification that was used in a primary data source.

2.1.1 Wildfires

A wildfire biomass consumption model was derived from estimates of the typical amount of forest biomass per unit area in each biogeoclimatic zone and of the proportion consumed in a typical wildfire.

Typical foliage, branch, stem, understory vegetation, woody debris, and forest floor biomass values were estimated for 11 vegetation types from a number of reports, and are given in Appendix 1. A weighted average biomass for each biogeoclimatic zone (Table 1) was calculated from these values and the proportion of these vegetation types that occur in each biogeoclimatic zone. The proportions were estimated from unpublished forest inventory summaries made by the B.C. Forest Service, Research Branch. The forest biomass values are mainly for mature stands, and may overestimate the average biomass of an entire zone. Where no data were available, some of the understory vegetation and standing debris biomass values were estimated.

The percentage of understory vegetation, woody debris, and forest floor consumed in surface and crown fires (Table 2) was estimated from the values reported for experimental fires by Alexander *et al.* (1991), Brown and DeByle (1989), Quintilio *et al.*, (1977, 1991) and from unpublished Canadian Forest Service data. The percentage foliage, branch, and stemwood consumption estimates were based on observations of large crown fires (greater than 200 ha). Values for large fires were used

because they accounted for 95% of the total area burned by wildfire in B.C. during 1981-90. The surface fire proportions were applied to the alpine, grass/shrub, and deciduous vegetation types, and the crown fire values to all other forest types. A weighted-average biomass

consumption was calculated for each biogeoclimatic zone from the vegetation biomass values and for the proportions of the types occurring by zone, assuming that the vegetation types burned in equal proportion.

TABLE 1. Estimates of vegetation biomass in British Columbia biogeoclimatic zones

| Biogeoclimatic zone | Biomass (t/ha) | | | | | | | Total |
|---------------------|----------------|----------|---------|-------------|-----------------|----------------|--------------|-------|
| | Stems | Branches | Foliage | Under story | Standing debris | Surface debris | Forest floor | |
| AT | 30 | 5 | 2 | 3.0 | 7 | 7 | 8 | 62 |
| BWBS | 87 | 13 | 6 | 1.6 | 14 | 21 | 53 | 196 |
| CDF | 376 | 38 | 10 | 3.6 | 54 | 104 | 35 | 621 |
| CWH | 536 | 64 | 16 | 3.1 | 54 | 174 | 53 | 900 |
| ESSF | 207 | 31 | 14 | 2.0 | 41 | 44 | 48 | 387 |
| ICH | 207 | 27 | 12 | 1.3 | 40 | 46 | 46 | 379 |
| IDF | 103 | 14 | 7 | 1.1 | 15 | 20 | 27 | 187 |
| MH | 305 | 50 | 17 | 1.2 | 106 | 65 | 103 | 647 |
| PP/BG | 39 | 10 | 5 | 1.7 | 8 | 16 | 15 | 95 |
| MS | 162 | 14 | 8 | 1.4 | 20 | 19 | 39 | 263 |
| SBS/ SBPS | 164 | 19 | 9 | 1.7 | 26 | 33 | 41 | 294 |
| SWB | 184 | 29 | 13 | 2.0 | 37 | 40 | 50 | 355 |

AT=Alpine Tundra; BWBS=Boreal White And Black Spruce; CDF=Coastal Douglas Fir; CWH=Coastal Western Hemlock; ESSF=Engelmann Spruce-Subalpine Fir; ICH=Interior Cedar Hemlock; IDF=Interior Douglas Fir; MH=Mountain Hemlock; PP/BG=Ponderosa Pine/Bunch Grass; MS=Montane Spruce; SBS/SBPS=Sub-Boreal Spruce/Sub-Boreal Pine-Spruce; SWB=Spruce Willow Birch.

TABLE 2. Estimates of biomass consumption in wildfires in British Columbia

| Type of fire | Percent consumption by component | | | | | | |
|--------------|----------------------------------|----------|---------|-------------|-----------------|----------------|--------------|
| | Stems | Branches | Foliage | Under-story | Standing debris | Surface debris | Forest floor |
| Surface | 0 | 0 | 0 | 65 | 0 | 85 | 35 |
| Crown | 2 | 10 | 50 | 65 | 5 | 60 | 60 |

2.1.2 Prescribed broadcast burns

Average fuel consumption values for prescribed broadcast burns in logging slash in each biogeoclimatic zone were derived from about 100 assessments carried out during 1984–92 (unpublished data on file at PFC) (Table 3) by the B.C. Forest Service, forest companies, the University of British Columbia, and the Canadian Forest Service. These measurements included the amount of woody debris present before and after burning and the forest floor depth reduction due to burning. Woody biomass consumption was determined by difference calculations. Equations describing cumulative forest floor mass as a function of depth (Canadian Forest Service unpublished data) were used to estimate forest floor biomass consumption from the depth-reduction measurements. The accuracy of the estimates varies between biogeoclimatic zones because there was an unequal number of assessments carried out in each zone.

2.1.3 Spot burns

There are few biomass data from logged sites in B.C. that were subsequently windrowed

or piled. It was assumed that the amount of debris per unit area on windrowed and piled sites was the same as on broadcast burn sites in the same biogeoclimatic zone, that no forest floor (LFH) material was included in the piles and windrows, and that 80% of the debris was consumed during burning on these sites (Table 3). The latter estimate is probably conservative; Blackwell *et al.* (1992) reported biomass consumption of 94–98% during prescribed burning of lodgepole pine debris piles, but the material in their study was of small size and therefore more likely to be consumed.

2.1.4 Landing burns

The amount of biomass contained in logging landing debris piles in B.C. is not well known. The amount of debris in landings was estimated using a landing debris/logged area-debris ratio of 0.035 t/t, (derived from measurements of Jones and Associates (1979)) and the average post logging biomass by biogeoclimatic zone. It was also assumed that 80% of the biomass in landing debris piles was consumed during burning.

TABLE 3. Mean wildland fire biomass consumption (t/ha) by biogeoclimatic zone

| Type of fire | Biogeoclimatic zone | | | | | | | | | | |
|-----------------------------|---------------------|------|-----|-----|------|-----|-----|-----|----|-------|------------------|
| | AT | BWBS | CDF | CWH | ESSF | ICH | IDF | MH | MS | PP/BG | SBS/S BPS SWB |
| Broadcast | – | 60 | 79 | 79 | 68 | 108 | 80 | 79 | 68 | 80 | 80 – |
| Landing ^a | – | 5 | 5 | 5 | 2 | 5 | 1 | 3 | 2 | 3 | 3 – |
| Spot | – | 136 | 136 | 136 | 80 | 128 | 41 | 95 | 80 | 95 | 95 – |
| Wildfire and Wildlife/range | 13 | 53 | 105 | 166 | 73 | 71 | 38 | 127 | 45 | 24 | 55 70 |

^a Values are per area harvested.

TABLE 4. Emission factors for wildland fires in British Columbia by type of fire

| Type of fire | Emission factors (g/kg) | | | | | | | |
|--|-------------------------|-----|-----------------|------------------|-----------------|-------------------|------------------|-----|
| | CO ₂ | CO | CH ₄ | N ₂ O | NO _x | PM _{2.5} | PM ₁₀ | TSP |
| Broadcast, wildfire, wildlife/range | 1625 | 101 | 5.7 | 0.29 | 1.5 | 12 | 13 | 17 |
| Spot, landing | as above | | | | | 4 | 4 | 6 |

2.2 Emission Factors

The yield of a combustion product per unit of fuel consumed (emission factor) varies over the burning period with combustion efficiency and between individual fires. Combustion efficiency (the proportion of carbon released as CO₂) is greater (and the proportion of other trace gases and particulates lower) during flaming and lower during smouldering combustion. The degree of flaming and smouldering combustion varies with fuel moisture content and with other burning conditions. However, typical fire-averaged emission factors have been developed for several fire and vegetation types in the United States (Ward *et al.* 1988). Fire-averaged emission factors for British Columbia fires (Table 4) were derived as weighted averages (by number of fires) of observations from a number of local studies, and from studies carried out in similar fire and vegetation types in Ontario and the Pacific Northwest (Appendix 2).

- Particulate values are from ground-based sampling of hand-lit broadcast burns and pile burns in Douglas-fir/western hemlock slash in western Washington and Oregon (Ward *et al.* 1988), and from aerial sampling of aerially ignited broadcast burns in Ontario and B.C. (PM_{3.5} data from the latter studies were included in the PM_{2.5} average) (Radke *et al.* 1992; Waggoner *et al.* 1992; Radke *et al.* 1990).
- The CO₂ value is based on the assumptions that 50% of forest biomass is carbon and that the average combustion efficiency (percentage C converted to CO₂) is 88%.

- CO and CH₄ values were derived from emission ratios (vol/vol CO₂) of Cofer *et al.* (1992), from aerial sampling of broadcast burns in Ontario and the above CO₂ emission factor, and from ground- and aerial-based sampling of broadcast burns in B.C. (Radke *et al.* 1992; Waggoner *et al.* 1992; Ward *et al.* 1992).
- NO_x and N₂O values are from aerial sampling of broadcast burns in Ontario and B.C. (Radke *et al.* 1992; Waggoner *et al.* 1992).

The same emission factors, mainly derived from broadcast burns, were used for all fire types, except that separate particulate values (Ward *et al.* 1988) were used for piled debris. This is because smoke from broadcast burns has been sampled more than smoke from other types of fires.

2.3 Fire Activity

2.3.1 Annual fire activity

The area burned annually by wildfire in each biogeoclimatic zone during 1981–90 was determined by intersecting the coordinates of all the fires occurring during this period (27 715) with a digital biogeoclimatic map, using overlay procedures in ARC-INFO. Coordinates and sizes of individual fires were obtained from the B.C. Forest Service (BCFS) Protection Branch wildfire reporting system.

The area of site preparation and landing burns within each biogeoclimatic zone was

estimated from BCFS annual reports and from silviculture databases. For the 1981–87 period, the areas of broadcast, windrow/pile, and landing burns, by biogeoclimatic zone and forest region, were obtained from the BCFS Silviculture Practices Branch History Records System. However, activities on Tree Farm Licences (TFL) were not included in this database, although they were included in the BCFS annual reports in summaries of the total area of Crown land treated by prescribed burning. Therefore, the History Record System data were used to determine the proportion of treated area by biogeoclimatic zone within each forest region for each type of fire. The total broadcast and windrow/pile burn area in each biogeoclimatic zone, by forest region, was estimated from these proportions and from the annual report totals. It was assumed that the proportion of area treated, by biogeoclimatic zone, was similar on TFL and non-TFL land within a forest region.

Landing burn activity was estimated from History Record System summaries and the ratio of area reported in History Record System/area reported in annual reports for broadcast burning, assuming that the same proportion of landing burns and broadcast burns are treated on TFL and non-TFL land. This procedure was used because landing burn activity was not included in BCFS annual reports.

For the 1987–90 period, silviculture burn activity was determined from both the History Records System (for the Small Business Forest Enterprise Program) and the Major Licensee Silviculture Information System (MLSIS) (for other major tenures). However, landing burn activity was not reported in MLSIS during this period, so landing burn averages were based on the preceding 1981–87 period only.

Wildlife and range burn activity was determined from unpublished BCFS Protection Branch annual summaries for 1982–90. However, the distribution of the area burned by biogeoclimatic zone within forest regions had to be estimated because primary data were not available.

No data on prescribed fire activity on private forest land were available for the study period. If the degree of burn activity is the same on private and Crown forest land, then the total broadcast, pile, and landing burn activity is underestimated by a few percent. However, no attempt was made to correct for these missing data.

2.3.2 Seasonal fire activity

The area treated by prescribed burns each week was obtained from BCFS weekly fire reports for 1990 and 1991; data for 1981–89 were not available. The area burned by wildfire each week was determined from the wildfire history records for this period. Biomass consumption was estimated from the area burned and from the average biomass consumption, by type of fire and forest region, during 1981–90 (Appendices 3 and 4).

2.3.3 Prehistoric fire activity

The average area burned annually by wildfire in each biogeoclimatic zone prehistorically was estimated from the area within each biogeoclimatic zone, from typical fire return intervals by vegetation type (Parminter 1992), and from the proportion of vegetation type in each biogeoclimatic zone. It was assumed that the total land area of the zone was vegetated, and that the average vegetation biomass in each zone was the same prehistorically as at present.

3 RESULTS AND DISCUSSION

3.1 Contemporary Biomass Consumption and Smoke Emissions

Estimates of average annual biomass consumption and smoke emissions during 1981–90 are given in Table 5. More-detailed breakdowns, by forest region and biogeoclimatic zone, are given in Appendices 4 and 5. Wildfires were the largest source of smoke emissions from wildland areas in B.C. during this period, followed by broadcast, wildlife habitat/range, spot, and landing burns. Wildfire was also the leading source of emissions in the Prince George, Vancouver, and Prince Rupert forest regions, although broadcast burning was the major wildland source in the other regions (Figure 1).

However, there was substantial annual variation in emissions production from all types of fire (Figure 2). The variation in wildfire emissions was three times that of prescribed fire. Coefficients of variation (standard deviation/mean) for annual biomass consumption were 125, 40, and 58% for wildfire, prescribed fire, and all wildland fires, respectively. Prescribed fire exceeded wildfire emissions in 6 of the 10 years.

The broadcast burn emission estimates are better than those for the other types of fire because their emissions chemistry is better known, and because the administrative records are more comprehensive and complete. The estimates for spot fires (piles and windrows) and landings should be considered as preliminary because the biomass estimates are tentative, and because particulate emissions factors from Washington, which may be overly conservative for conditions in British Columbia, were used. Further study of PM_{2.5} and PM₁₀ emissions from debris piles would help to improve future estimates.

There is substantial variability in biomass consumption within fire and forest types. However, broadcast, wildlife range, and wildfire biomass consumption estimates could be improved by using existing equations that relate fuel consumption to fuel load and burning conditions on an individual fire basis. Many of these data are currently recorded in waste surveys and burning permits, but are not centrally available.

The particulate emission factors used for wildfires in this study were much lower than those reported by Nance *et al.* (1993), and may be too conservative. However, more wildfire data are needed to address this question because they only examined one fire.

TABLE 5. Average annual biomass consumption, particulate, and trace gas emissions from wildland fires in British Columbia during 1981–90

| Type of fire | Average annual biomass consumption / smoke emissions (kilotonnes) | | | | | | | | |
|----------------|---|-------------------|------------------|-----|-----------------|-------|-----------------|-----------------|------------------|
| | Biomass | PM _{2.5} | PM ₁₀ | TSP | CO ₂ | CO | CH ₄ | NO _x | N ₂ O |
| Broadcast | 3 335 | 40 | 43 | 57 | 5 420 | 338 | 19 | 4 | 0.97 |
| Landing | 96 | 0.4 | 0.4 | 0.6 | 158 | 10 | 0.6 | 0.1 | 0.03 |
| Spot | 1 325 | 5 | 5 | 8 | 2 153 | 134 | 8 | 2 | 0.38 |
| Wildlife/range | 2 339 | 28 | 30 | 40 | 2 832 | 236 | 13 | 3 | 0.68 |
| Wildfire | 5 599 | 67 | 73 | 95 | 9 098 | 566 | 32 | 7 | 1.62 |
| Total | 12 694 | 141 | 152 | 200 | 19 661 | 1 283 | 72 | 17 | 3.68 |

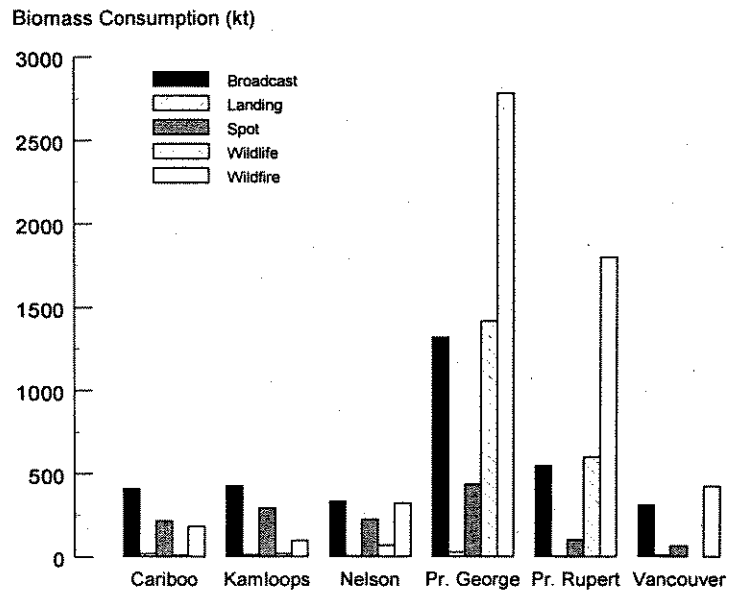


FIGURE 1. Average annual biomass consumption in wildland fires in British Columbia (1981-90) by forest region and fire type.

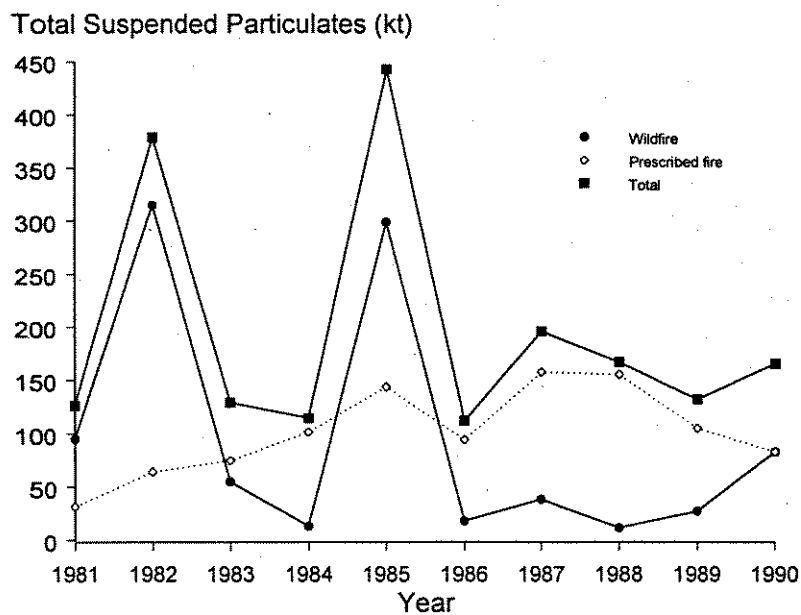


FIGURE 2. Average annual total suspended particulate production from wildland fires in British Columbia (1981-90).

Previous studies (Levelton and Associates 1990, 1991; Concord Environmental 1991) suggested that prescribed fire contributed 16, 3, 6, and 3% of total anthropogenic CO₂, CH₄, NO_x, and N₂O emissions, respectively, in British Columbia. Estimates presented in this report of CO₂ and NO_x production from prescribed fires during 1981–90 are within 10% of those of Levelton and Associates (1990) and Concord Environmental (1991), for 1987 and 1985, respectively. However, estimates of prescribed fire CH₄ and N₂O production are about two and four times greater, respectively, than those of Levelton and Associates (1991) and Concord Environmental (1991). This is probably due to the use of a long-term average rather than a single reference year, and possibly because of different fuel consumption values and emission factors. Estimates of wildfire emissions are also substantially larger than indicated by these previous studies.

CO and CO₂ emissions may be used to estimate the production of other trace gases. Ward *et al.* (1993) estimated the production of several air-toxic compounds (e.g., acrolein and formaldehyde) from biomass burning in the U.S. from their relationship with CO concentrations in laboratory burns and from biomass-burning CO production. Similarly, Mano and Andreae (1994) estimated the production of methyl bromide from global biomass burning from laboratory-derived CH₄Br/CO₂ ratios and estimates of global biomass-burning CO₂ emissions. Methyl bromide, which can break down stratospheric ozone, is known to be produced by industrial and natural oceanic sources, but has only recently been found in smoke from biomass burning.

The effects of wildland fire emissions on air quality are not necessarily directly related to, or in proportion to, the amounts produced. Though visibility decreases exponentially in relation to fine particle concentrations (Malm 1992), particle concentrations are strongly affected by atmospheric stability, wind speed, and topography, in addition to emissions production. The magnitude and duration of exposure are important factors concerning the effect of fine particulate and other air toxic

compound concentrations on health and is further influenced by the proximity of emissions sources to sensitive areas. Sandberg and Dost (1990) present estimates that, while not conclusive, suggest low health risks from PAH and aldehydes in prescribed fire smoke in the Pacific Northwest because of low exposures. It was not possible to examine the distribution of fire sources in this study, except at the broad forest region level. Much more detailed modelling that incorporates atmospheric topographic factors would be required to address air quality questions.

Fire size is also an important factor with regard to effects on air quality, because reaction intensities and convective forces that help to vent and disperse the smoke tend to increase with fire size. However, it was not possible to characterize the size distribution or reaction intensity of fires in this study.

3.2 Seasonal Distribution of Emissions

Biomass consumption between April and November, by week, was examined for the years 1990 and 1991 (Figure 3) as an index of the seasonal distribution of emissions. The data are likely complete for wildfires, wildlife/range, and broadcast burns, but some spot and landing burns may have been excluded if they occurred outside of the reporting period. The areas burned by wildfire are given for the week the fire was reported, although some large fires may have burned for more than one week. The seasonal variation in biomass consumption for particular fire types could not be accounted for.

The graphs suggest that the seasonal distribution of emissions is episodic rather than continuous. These episodes are related to weather conditions that favour wildfire occurrence or prescribed burning. Although emissions from individual fires generally occur over a few hours in the case of broadcast burns, and up to a few days in the case of larger wildfires and debris piles, emissions may be released from a number of successive fires within an airshed during favourable burning

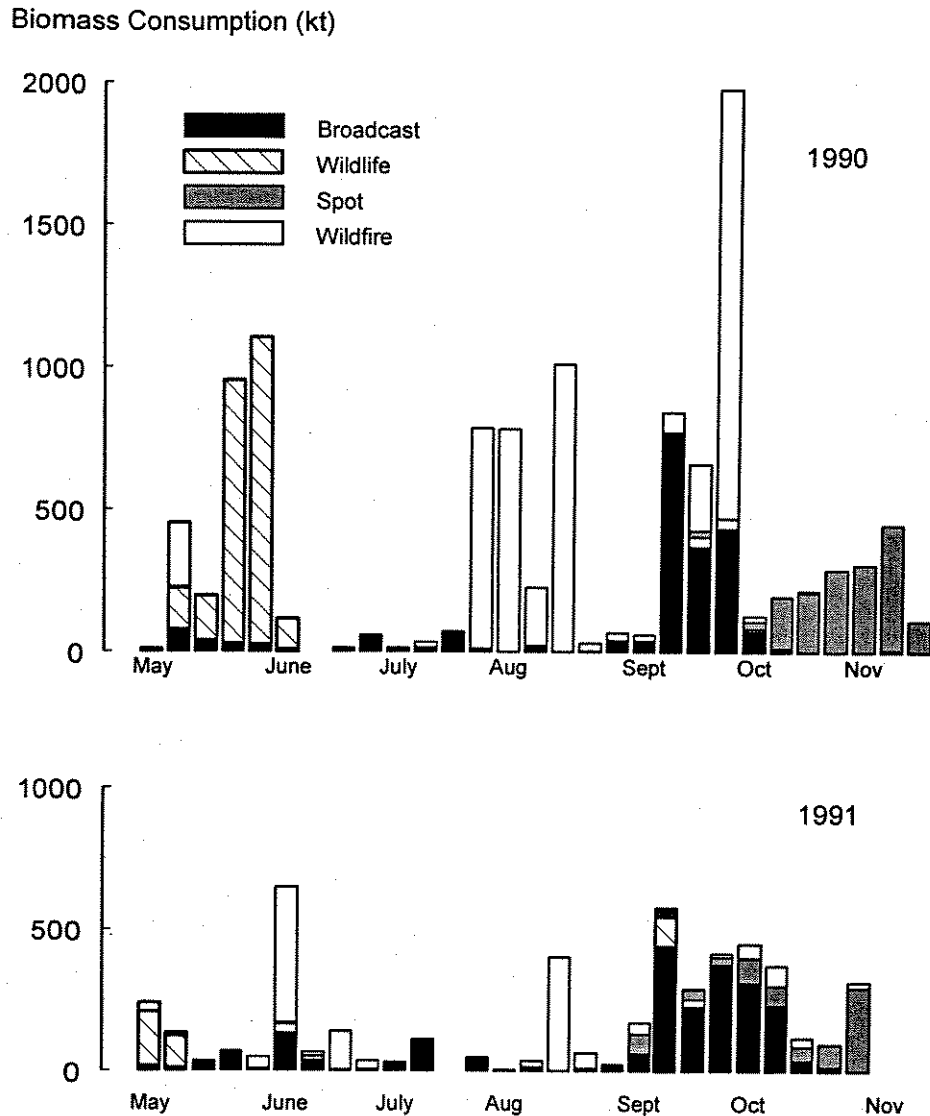


FIGURE 3. Biomass consumption from wildland fires in British Columbia, by week, during 1990 and 1991.

conditions, and so potentially affect air quality for a few days to a few weeks.

The data for 1990-91 also suggest that emissions tend to be associated with different types of fire at different times of the year. Most wildlife habitat/range burns occurred in May, wildfires in July or August, broadcast burns in

September, and spot burns in October and November.

The seasonal distribution of emissions is also important in relation to seasonal weather patterns. In British Columbia, atmospheric conditions are generally more favourable for venting smoke away from the surface in the

summer months (June–Sept.), and poorer during the rest of the year, especially in valleys. This suggests that smoke dispersion from spot fires and landing burns (which tend to be carried out during the fall) is probably poorer than from the other types of fire.

3.3 Prehistoric Biomass Consumption and Smoke Emissions

Biomass consumption and smoke emissions from prehistoric wildland fires in B.C. (Table 6) were estimated to be between 3 and 6 times contemporary amounts. The reduction in emissions is due to substantially less wildfire activity in the contemporary period, and this, in turn, is probably due mainly to fire suppression. While these estimates should be considered speculative (because prehistoric fire activity cannot be precisely quantified over such large areas) it is certain that large amounts of smoke were produced. However, it is also likely that there was significant variation in fire activity and smoke production from year to year, with some years having a few small fires and good air quality, and other years having more, larger fires with persistent smouldering and poor air quality.

4 CONCLUSIONS

The objective of this study was to develop estimates of smoke emissions from wildland fires in British Columbia in contemporary and prehistoric periods.

Wildland fires in B.C. are a significant source of particulates and trace gases. However, the effects of these emissions on air quality require further study because they also depend on the proximity of the fires to sensitive areas, and on fire and atmospheric conditions that affect smoke dispersion.

Estimates of prehistoric emissions production are more speculative; however, it is

Fahnestock and Agee (1983) estimated that prehistoric wildland fire emissions in western Washington were about 1.25 times greater than present levels. The larger difference in this study is probably because of the higher proportion of interior forest types in B.C., which have likely been more strongly affected by fire suppression than coastal forests.

Emissions from wildfires, both presently and historically, are of interest in the public policy and regulatory context where background levels are of considerable concern. Prescribed fire emissions have usually been treated as anthropogenic sources, although wildfires are usually considered natural sources. However, in environments subject to wildfire, there may be limits on how much or how long fire activity and smoke production can be suppressed. If biomass accumulates due to fire suppression, it may not be possible, and perhaps not ecologically desirable, to suppress fire indefinitely over wide areas unless other methods of biomass reduction are used. Fire suppression and restrictions on prescribed burning in environments that are naturally subject to frequent low-intensity fires may be contributing to biomass accumulation, and to more severe wildfires with more significant effects on air quality (National Commission on Wildfire Disasters 1994).

certain that there was substantial fire activity and smoke levels in prehistoric times. It is suggested that fire suppression has substantially reduced ambient smoke levels; however, a greater understanding of the ecological and fire-management consequences of altering historical fire regimes is needed.

Analysis of several primary databases was required to develop the emissions estimates for the contemporary period. While this was a rather convoluted process, the types of data required to inventory wildland fire emissions in British Columbia were identified.

Future inventories could be improved by the following:

- better definition of particulate emission factors for spot and landing fires and wildfires;

- better definition of biomass consumption in spot and landing fires; and
- improving access to data on location, fuel load, and burning conditions for the major types of fire. These data are also required for smoke dispersion modelling.

TABLE 6. Biomass consumption and particulate emissions from prehistoric wildfires in British Columbia

| Biogeo-climatic zone | Land area (hectares) | Type of fire ^a | Fire return interval | | Average annual | | | | | |
|----------------------|----------------------|---------------------------|----------------------|-----|------------------------|-----------|----------------------------------|--------|----------------------------|-------|
| | | | | | area burned (hectares) | | biomass consumption (kilotonnes) | | TSP emissions (kilotonnes) | |
| AT | 17 489 200 | S | 300 | 400 | 43 723 | 58 297 | 547 | 729 | 9 | 12 |
| BG | 323 900 | S | 5 | 15 | 21 593 | 64 780 | 155 | 466 | 3 | 8 |
| BWBS Sbb | 4 476 592 | S+C | 75 | 125 | 35 813 | 59 688 | 2 417 | 4 029 | 41 | 69 |
| At | 4 245 152 | S+C | 100 | 150 | 28 301 | 42 452 | 722 | 1 083 | 12 | 18 |
| PlSw | 6 538 353 | S+C | 150 | 200 | 32 692 | 43 589 | 1 997 | 2 663 | 34 | 45 |
| CDF | 162 800 | S+C | 100 | 300 | 543 | 1 628 | 57 | 171 | 1 | 3 |
| CWH | 9 995 100 | S+C | 150 | 350 | 28 557 | 66 634 | 4 738 | 11 055 | 81 | 188 |
| ESSF | 13 252 900 | S+C | 200 | 300 | 44 176 | 66 265 | 3 225 | 4 837 | 55 | 82 |
| ICH | 5 240 500 | S+C | 150 | 250 | 20 962 | 34 937 | 1 495 | 2 491 | 25 | 42 |
| IDF | 4 375 400 | S | 10 | 20 | 218 770 | 437 540 | 13 979 | 27 959 | 238 | 475 |
| | 4 375 400 | S+C | 150 | 250 | 17 502 | 29 169 | 485 | 808 | 8 | 14 |
| MH | 4 119 100 | S+C | 350 | 450 | 9 154 | 11 769 | 1 159 | 1 490 | 20 | 25 |
| MS | 2 633 900 | S+C | 175 | 275 | 9 578 | 15 051 | 431 | 677 | 7 | 12 |
| PP | 338 200 | S | 5 | 15 | 22 547 | 67 640 | 550 | 1 650 | 9 | 28 |
| SBS | 10 267 200 | S+C | 100 | 150 | 68 448 | 102 672 | 3 799 | 5 698 | 65 | 97 |
| SBPS | 2 589 800 | S+C | 125 | 175 | 14 799 | 20 718 | 642 | 899 | 11 | 15 |
| SWB | 7 802 200 | S+C | 200 | 350 | 22 292 | 39 011 | 1 558 | 2 727 | 27 | 46 |
| BC | 98 225 697 | | | | 639 450 | 1 161 840 | 37 956 | 69 432 | 646 | 1 179 |

^a Type of fire: S=surface fire; C=crown fire.

^b Sb = black spruce; At = trembling aspen; PlSw = lodgepole pine / white spruce

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APPENDIX 1. Biomass of some vegetation types occurring in British Columbia.

| Vegetation type | Location | Stand age (yrs) | Biomass (t/ha) | | | | | | | Reference |
|------------------------------|------------|-----------------|----------------|----------|---------|-------------|-----------------|----------------|--------------|--|
| | | | stems | branches | foliage | under-story | standing debris | surface debris | forest floor | |
| Alpine | CO | | | | | 2.0 | | | | Anderson <i>et al.</i> 1979 |
| Black spruce | AL lowland | 51 | | 16 | | 1.5 | 2 | 3 | 102 | Barney and Van Cleve 1972 |
| | upland | 55 | | 24 | | 1.7 | 1 | 2 | 122 | Van Cleve <i>et al.</i> 1981 |
| | AL muskeg | | 8 | 2 | 4 | 1.5 | 2 | | 82 | |
| | upland | | 14 | 3 | 5 | 1.7 | 2 | | 123 | |
| | AL | 56-130 | | | | | | | 82 | Zasada <i>et al.</i> 1977 |
| Grass / shrub | BC | | | | | 1.4 | | | | Tisdale 1947 |
| | BC | | | | | 3.4 | | | | Nicholson 1992 |
| | | | | | | | 4.8 | | | |
| Aspen | AB | | | | | | | 3.7 | 28.7 | Quintilio <i>et al.</i> 1991 |
| | | | | | | 0.9 | | 54.1 | 1.4 | Brown and DeByle 1989 |
| | | | | | | 0.2 | | 10.8 | 8.3 | |
| | | | | | | 2.0 | | 25.9 | 8.6 | |
| | | | | | | 1.4 | | 10.8 | 8.9 | |
| | | | | | | 2.2 | | 41.1 | 10.6 | |
| Western red cedar (interior) | ID | ca 100 | 433 | 45 | 20 | | | | | Hanley 1976 |
| | WA/ID/MT | | | | | | | 75 | | Brown and See 1981 |
| | ID | 20-400 | | | | | | 41 | 74 | Habeck 1983 |
| | ID | <450 | | | | 1.0 | | 9 | 55 | Habeck 1974 |
| | | >450 | | | | 0.4 | | 226 | 115 | |
| Douglas-fir (coastal) | OR | | 645 | 53 | 12 | 7 | | 215 | 51 | Grier and Logan 1977 |
| | OR | 450 | 472 | 49 | 9 | | | | | Grier <i>et al.</i> 1974 |
| | WA | 50 | 134 | 20 | 11 | 2.2 | | | 14 | Bigger and Cole 1983 |
| | BC | 120 | | | | | | | 52 | de Catanzaro 1979 |
| | dry/mesic | 120 | | | | | | | 30 | |
| | | moist | 120 | | | | | | | |
| | BC | 100+ | | | | | | | 27 | Binkley <i>et al.</i> 1982 |
| | WA | | | | | | 49 | 49 | | Pickford <i>et al.</i> 1980 |
| | | 100 | | | | | 34 | 108 | | Franklin in Harmon <i>et. al.</i> 1986 |
| | | 130 | | | | | | 42 | 65 | |
| | | 250 | | | | | | 80 | 93 | |
| | | 450 | | | | | | 84 | 82 | |
| | | 750 | | | | | 108 | 97 | | |
| | 1000 | | | | | 81 | 115 | | | |

APPENDIX 1. (continued)

| Vegetation type | Location | Stand age (yrs) | Biomass (t/ha) | | | | | | | Reference |
|-----------------------------------|-----------------|-----------------|----------------|----------|---------|-------------|-----------------|----------------|--------------|------------------------------|
| | | | stems | branches | foliage | under-story | standing debris | surface debris | forest floor | |
| Douglas-fir | WA/ID/MT | | | | | | | 23 | | Brown and See 1981 |
| (interior) | BC | | | | | 1.4 | | 31 | | Smail 1980 |
| | BC | | 60 | 17 | 19 | 0.7 | | 10 | 20 | Braumandl <i>et al.</i> 1995 |
| Engelmann spruce /subalpine fir | BC | | 301 | 55 | 20 | 2.3 | 58 | 63 | 54 | Feller and Hamilton 1994 |
| | subhygric mesic | | 173 | 34 | 14 | 2.6 | 39 | 39 | 43 | |
| | WA/ID/MT | | | | | | | 56 | | Brown and See 1981 |
| Lodgepole pine | BC | | 181 | 10 | 5 | | | | 41 | Kimmins 1974 |
| | BC xeric | 75 | 108 | 6 | 4 | | | | | Comeau and Kimmins 1989 |
| | mesic | 75 | 240 | 14 | 9 | | | | | |
| | WA/ID/MT | | | | | | | 13 | | Brown and See 1981 |
| Mountain hemlock /amabilis fir | WA | 180 | 356 | 68 | 22 | 0.2 | 157 | 75 | 150 | Grier <i>et al.</i> 1981 |
| | BC | | 396 | 56 | 16 | 0.6 | | | | Krumlik 1974; Yari 1980 |
| Ponderosa pine | BC | | | | | 0.7 | | 15 | 19 | Nyberg 1979 |
| | ID warm moist | | | | | 1.1 | | 28 | 16 | Habeck 1974 |
| | WA/ID/MT | | | | | 3.1 | | 4 | 21 | |
| | | | | | | | | 29 | | Brown and See 1981 |
| | BC | | 42 | 12 | 10 | 0.3 | | 40 | 29 | Braumandl <i>et al.</i> 1995 |
| Western hemlock/ western redcedar | WA | | 840 | 50 | 8 | 4 | | 212 | 80 | Grier 1976 |
| | WA | 110 | 534 | 66 | 22 | 0.7 | 45 | 155 | 32 | Agee and Huff 1987 |
| | | 181 | 492 | 65 | 21 | 2.9 | 41 | 131 | 32 | |
| | | 515 | 933 | 154 | 21 | 6.2 | 93 | 459 | 95 | |

APPENDIX 2. Fire-averaged emission factors for some biomass fires in North America.

| Fire / vegetation type (no.) ^a | Location | Emission factor (g/kg) | | | | | | | | | Ref. ^b |
|---|----------|------------------------|-----------------|------------------|--------------------------|-----------------|-----|-----------------|-----------------|------------------|-------------------|
| | | PM _{2.5/3.5} | PM ₅ | PM ₁₀ | TSP/ PM ₄₀ | CO ₂ | CO | CH ₄ | NO _x | N ₂ O | |
| Broadcast Burns | | | | | | | | | | | |
| WRC/WH (1) | BC | 13 | | | 23 | 1660 | 83 | 4 | | 0.04 | 1 |
| WRC/DF & ES/SF (2) | BC | 12 | | | | 1627 | 85 | 6 | 0.42 | 0.28 | 2 |
| WRC/DF/SF (1) | BC | 13 | | | | 1528 | 142 | 10 | | | 3 |
| BS/JP & PB/P (3) | ONT | | | | | | 112 | 7 | | 0.39 | 4 |
| BS/JP & PB/P/BF (4) | ONT | 15 | | | 14 | 1629 | 100 | 4 | | 0.27 | 1 |
| BS/JP (1) | ONT | | 12 | | | 1673 | 86 | | 2.18 | | 5 |
| DF (6) | WA/OR | 4 | | | 12 | | | | | | 6 |
| DF/WH/WRC (15) | WA | 12 | | 13 | 17 | | | | | | 7 |
| Pile Burns | | | | | | | | | | | |
| Clean piles | PNW | 4 | | 4 | 6 | | | | | | 7 |
| Including 10–30% mineral soil or 25% organic soil | PNW | | | | 30 | | | | | | |
| Prescribed burns of natural fuels | | | | | | | | | | | |
| Chapparral (2) | CA | | | | | | 56 | 3 | | 0.39 | 4 |
| Chapparral/chamise (3) | CA | | | | | 1657 | 61 | 2 | 6.50 | 0.25 | 1 |
| Chapparral | SW US | 8 | | 9 | 15 | | | | | | 7 |
| Palmetto-galberry | SE US | | | 15 | 16 | | | | | | |
| Grass | SE US | | | 10 | 10 | | | | | | |
| Wetlands (2) | FLA | | | | | | 49 | 2 | | 0.47 | |
| Wildfires | | | | | | | | | | | |
| DF/true fir/pine slash (2) | OR | 13 | | | 31 | 1631 | 96 | 3 | 2.00 | 0.34 | 1 |
| BS (1) | AL | 22 | | | | 1640 | 81 | 3 | 1.50 | 0.14 | 8 |

^a WC = western redcedar; WH = western hemlock; DF = Douglas-fir; ES = Engelmann spruce; SF = subalpine fir; BS = black spruce JP = jack pine; PB = paper birch; P = poplar

^b Numbers indicate the following references: 1–Radke *et al.* 1992; 2–Wagonner *et al.* 1992; 3–Ward *et al.* 1992; 4–Cofer *et al.* 1992; 5–Susott *et al.* 1990; 6–Radke *et al.* 1990; 7–Ward *et al.* 1988; 8–Nance *et al.* 1993.

APPENDIX 3. Average annual area burned by wildland fires in British Columbia (1981-90).

| Burn type | Region | Area burned by biogeoclimatic zone (hectares) | | | | | | | | | | | Total |
|---------------------------------|--------------|---|----------------|------------|--------------|---------------|---------------|---------------|------------|--------------|------------|---------------|----------------------|
| | | AT | BWBS | CDF | CWH | ESSF | ICH | IDF | MH | MS | PP/BG | SBS/SBPS | |
| Broadcast | Cariboo | 0 | 0 | 0 | 0 | 2 186 | 1 377 | 4 | 0 | 29 | 0 | 1 349 | 0 4 945 |
| | Kamloops | 0 | 0 | 0 | 27 | 1 996 | 2 185 | 214 | 1 | 392 | 8 | 92 | 0 4 915 |
| | Nelson | 0 | 0 | 0 | 0 | 1 247 | 2 242 | 8 | 0 | 87 | 0 | 0 | 0 3 584 |
| | Pr. George | 0 | 282 | 0 | 0 | 2 380 | 902 | 0 | 0 | 0 | 0 | 13 067 | 0 16 631 |
| | Pr. Rupert | 0 | 0 | 0 | 198 | 346 | 1 478 | 0 | 0 | 0 | 0 | 4 357 | 0 6 379 |
| | Vancouver | 0 | 0 | 293 | 3 568 | 4 | 0 | 22 | 12 | 0 | 0 | 0 | 0 3 899 |
| | Total | 0 | 282 | 293 | 3 793 | 8 159 | 8 184 | 248 | 13 | 508 | 8 | 18 865 | 0 40 353 |
| Landing | Cariboo | 0 | 0 | 0 | 0 | 433 | 442 | 3 230 | 0 | 342 | 0 | 5 245 | 0 9 692 |
| | Kamloops | 0 | 0 | 0 | 0 | 1 880 | 931 | 2 599 | 0 | 1 475 | 64 | 71 | 0 7 020 |
| | Nelson | 0 | 0 | 0 | 0 | 326 | 801 | 178 | 0 | 100 | 0 | 0 | 0 1 405 |
| | Pr. George | 0 | 2 723 | 0 | 0 | 603 | 83 | 0 | 0 | 0 | 0 | 7 573 | 0 10 982 |
| | Pr. Rupert | 0 | 19 | 0 | 252 | 0 | 193 | 0 | 0 | 0 | 0 | 597 | 0 1 061 |
| | Vancouver | 0 | 0 | 0 | 2 624 | 0 | 0 | 72 | 270 | 0 | 0 | 0 | 0 2 966 |
| | Total | 0 | 2 742 | 0 | 2 876 | 3 242 | 2 450 | 6 079 | 270 | 1 917 | 64 | 13 486 | 0 33 126 |
| Spot | Cariboo | 0 | 0 | 0 | 0 | 177 | 270 | 24 | 0 | 44 | 0 | 1 690 | 0 2 205 |
| | Kamloops | 0 | 0 | 0 | 1 | 728 | 862 | 465 | 0 | 1 221 | 2 | 69 | 0 3 348 |
| | Nelson | 0 | 0 | 0 | 0 | 724 | 1 211 | 51 | 0 | 96 | 0 | 0 | 0 2 082 |
| | Pr. George | 0 | 570 | 0 | 0 | 315 | 154 | 0 | 0 | 0 | 0 | 3 272 | 0 4 311 |
| | Pr. Rupert | 0 | 4 | 0 | 123 | 8 | 75 | 0 | 0 | 0 | 0 | 775 | 0 985 |
| | Vancouver | 0 | 0 | 74 | 394 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 0 471 |
| | Total | 0 | 574 | 74 | 518 | 1 952 | 2 572 | 541 | 2 | 1 361 | 2 | 5 806 | 0 13 402 |
| Wildlife/ range ^a | Cariboo | 0 | 0 | 0 | 0 | 0 | 0 | 234 | 0 | 0 | 0 | 0 | 0 234 |
| | Kamloops | 0 | 0 | 0 | 0 | 0 | 0 | 510 | 0 | 0 | 57 | 0 | 0 567 |
| | Nelson | 0 | 0 | 0 | 0 | 0 | 0 | 1 739 | 0 | 193 | 0 | 0 | 0 1 932 |
| | Pr. George | 0 | 29 624 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 29 624 |
| | Pr. Rupert | 0 | 12 479 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 12 479 |
| | Vancouver | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 0 |
| | Total | 0 | 42 103 | 0 | 0 | 0 | 0 | 2 483 | 0 | 193 | 57 | 0 | 0 44 836 |
| Wildfire | Cariboo | 64 | 0 | 0 | 232 | 185 | 122 | 724 | 0 | 435 | 16 | 1 346 | 0 3 124 |
| | Kamloops | 429 | 0 | 0 | 9 | 451 | 127 | 848 | 0 | 102 | 401 | 30 | 0 2 397 |
| | Nelson | 1 653 | 0 | 0 | 0 | 2 493 | 247 | 2 258 | 0 | 220 | 141 | 0 | 0 7 012 |
| | Pr. George | 3 848 | 38 454 | 0 | 0 | 3 235 | 61 | 1 | 0 | 0 | 0 | 3 711 | 3 562 52 872 |
| | Pr. Rupert | 1 027 | 22 070 | 0 | 97 | 203 | 208 | 0 | 73 | 0 | 0 | 2 735 | 5 848 32 261 |
| | Vancouver | 167 | 0 | 12 | 2 098 | 78 | 0 | 28 | 427 | 0 | 0 | 180 | 0 2 990 |
| | Total | 7 188 | 60 524 | 12 | 2 436 | 6 645 | 765 | 3 859 | 500 | 757 | 558 | 8 002 | 9 410 100 656 |
| Total | | 7 188 | 106 225 | 379 | 9 623 | 19 998 | 13 971 | 13 210 | 785 | 4 736 | 689 | 46 159 | 9 410 232 373 |

^a The distribution of wildlife /range fire activity within each forest region are author's estimates.

APPENDIX 4. Average annual biomass consumption by wildland fires in British Columbia (1981-90).

| | | Biomass consumption by biogeoclimatic zone (kilotonnes) | | | | | | | | | | | | |
|---------------------------------|--------------|---|----------------|-------------|--------------|--------------|----------------|--------------|-------------|--------------|-------------|----------------|--------------|-----------------|
| Burn type | Region | AT | BWBS | CDF | CWH | ESSF | ICH | IDF | MH | MS | PP/ BG | SBS/ SBPS | SWB | Total |
| Broadcast | Cariboo | 0.0 | 0.0 | 0.0 | 0.0 | 148.8 | 148.0 | 0.3 | 0.0 | 2.0 | 0.0 | 107.5 | 0.0 | 406.6 |
| | Kamloops | 0.0 | 0.0 | 0.0 | 2.1 | 135.9 | 234.9 | 17.2 | 0.1 | 26.7 | 0.6 | 7.3 | 0.0 | 424.8 |
| | Nelson | 0.0 | 0.0 | 0.0 | 0.0 | 84.9 | 241.0 | 0.6 | 0.0 | 5.9 | 0.0 | 0.0 | 0.0 | 332.4 |
| | Pr. George | 0.0 | 16.9 | 0.0 | 0.0 | 162.1 | 97.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1 041.4 | 0.0 | 1 317.4 |
| | Pr. Rupert | 0.0 | 0.0 | 0.0 | 15.7 | 23.6 | 158.9 | 0.0 | 0.0 | 0.0 | 0.0 | 347.2 | 0.0 | 545.4 |
| | Vancouver | 0.0 | 0.0 | 23.2 | 282.6 | 0.3 | 0.0 | 1.8 | 0.9 | 0.0 | 0.0 | 0.0 | 0.0 | 308.8 |
| | Total | 0.0 | 16.9 | 23.2 | 300.4 | 555.6 | 879.8 | 19.9 | 1.0 | 34.6 | 0.6 | 1 503.4 | 0.0 | 3 335.4 |
| Landing | Cariboo | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 2.0 | 2.9 | 0.0 | 0.8 | 0.0 | 15.7 | 0.0 | 22.4 |
| | Kamloops | 0.0 | 0.0 | 0.0 | 0.0 | 4.5 | 4.3 | 2.3 | 0.0 | 3.5 | 0.2 | 0.2 | 0.0 | 15 |
| | Nelson | 0.0 | 0.0 | 0.0 | 0.0 | 0.8 | 3.7 | 0.2 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 4.9 |
| | Pr. George | 0.0 | 12.8 | 0.0 | 0.0 | 1.4 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | 22.7 | 0.0 | 37.3 |
| | Pr. Rupert | 0.0 | 0.1 | 0.0 | 1.2 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 1.8 | 0.0 | 3.2 |
| | Vancouver | 0.0 | 0.0 | 0.0 | 12.3 | 0.0 | 0.0 | 0.1 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 13.2 |
| | Total | 0.0 | 12.9 | 0.0 | 13.5 | 7.7 | 10.5 | 5.5 | 0.8 | 4.5 | 0.2 | 40.4 | 0.0 | 96 |
| Spot | Cariboo | 0.0 | 0.0 | 0.0 | 0.0 | 14.1 | 34.5 | 1.0 | 0.0 | 3.5 | 0.0 | 160.2 | 0.0 | 213.3 |
| | Kamloops | 0.0 | 0.0 | 0.0 | 0.1 | 58.1 | 110.2 | 19.3 | 0.0 | 97.4 | 0.2 | 6.5 | 0.0 | 291.8 |
| | Nelson | 0.0 | 0.0 | 0.0 | 0.0 | 57.8 | 154.9 | 2.1 | 0.0 | 7.6 | 0.0 | 0.0 | 0.0 | 222.4 |
| | Pr. George | 0.0 | 77.7 | 0.0 | 0.0 | 25.1 | 19.7 | 0.0 | 0.0 | 0.0 | 0.0 | 310.2 | 0.0 | 432.7 |
| | Pr. Rupert | 0.0 | 0.5 | 0.0 | 16.7 | 0.6 | 9.6 | 0.0 | 0.0 | 0.0 | 0.0 | 73.5 | 0.0 | 100.9 |
| | Vancouver | 0.0 | 0.0 | 10.1 | 53.7 | 0.0 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 64 |
| | Total | 0.0 | 78.2 | 10.1 | 70.5 | 155.7 | 328.9 | 22.4 | 0.2 | 108.5 | 0.2 | 550.4 | 0.0 | 1 325.1 |
| Wildlife/ range ^a | Cariboo | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 8.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 8.8 |
| | Kamloops | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 19.2 | 0.0 | 0.0 | 1.4 | 0.0 | 0.0 | 20.6 |
| | Nelson | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 65.5 | 0.0 | 8.7 | 0.0 | 0.0 | 0.0 | 74.2 |
| | Pr. George | 0.0 | 1 573.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1 573 |
| | Pr. Rupert | 0.0 | 662.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 662.6 |
| | Vancouver | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Total | 0.0 | 2 235.6 | 0.0 | 0.0 | 0.0 | 0.0 | 93.5 | 0.0 | 8.7 | 1.4 | 0.0 | 0.0 | 2 339.2 |
| Wildfire | Cariboo | 0.8 | 0.0 | 0.0 | 38.5 | 13.5 | 8.7 | 27.3 | 0.0 | 19.6 | 0.4 | 73.3 | 0.0 | 182.1 |
| | Kamloops | 5.4 | 0.0 | 0.0 | 1.5 | 32.9 | 9.0 | 32.0 | 0.0 | 4.6 | 9.8 | 1.6 | 0.0 | 96.8 |
| | Nelson | 20.7 | 0.0 | 0.0 | 0.0 | 182.0 | 17.6 | 85.1 | 0.0 | 9.9 | 3.4 | 0.0 | 0.0 | 318.7 |
| | Pr. George | 48.1 | 2 041.9 | 0.0 | 0.0 | 236.1 | 4.3 | 0.0 | 0.0 | 0.0 | 0.0 | 202.3 | 249.0 | 2 781.7 |
| | Pr. Rupert | 12.8 | 1 171.9 | 0.0 | 16.0 | 14.8 | 14.8 | 0.0 | 9.3 | 0.0 | 0.0 | 149.0 | 408.7 | 1 797.3 |
| | Vancouver | 2.1 | 0.0 | 1.2 | 348.1 | 5.7 | 0.0 | 1.0 | 54.1 | 0.0 | 0.0 | 9.8 | 0.0 | 422 |
| | Total | 89.9 | 3 213.8 | 1.2 | 404.1 | 485 | 54.4 | 145.4 | 63.4 | 34.1 | 13.6 | 436 | 657.7 | 5 598.6 |
| Total | | 89.9 | 5 557.4 | 34.5 | 788.5 | 1 204 | 1 273.6 | 286.7 | 65.4 | 190.4 | 16 | 2 530.2 | 657.7 | 12 694.3 |

^a The distribution of wildlife /range fire activity within each forest region are author's estimates.

APPENDIX 5. Average annual trace gas and particulate emissions from wildland fires in B.C. (1981-90).

| Burn type | Region | Trace gas and particulate emissions (kilotonnes) | | | | | | | |
|--------------------|--------------|--|----------------|-----------------|------------------|-----------------|-------------------|------------------|---------------|
| | | CO ₂ | CO | CH ₄ | N ₂ O | NO _x | PM _{2.5} | PM ₁₀ | TSP |
| Broadcast | Cariboo | 661 | 41.7 | 2.32 | 0.118 | 0.53 | 4.88 | 5.29 | 6.91 |
| | Kamloops | 690 | 42.9 | 2.42 | 0.123 | 0.55 | 5.10 | 5.52 | 7.22 |
| | Nelson | 540 | 33.6 | 1.90 | 0.096 | 0.43 | 3.99 | 4.32 | 5.65 |
| | Pr. George | 2 141 | 133.1 | 7.51 | 0.382 | 1.71 | 15.81 | 17.13 | 22.40 |
| | Pr. Rupert | 886 | 55.1 | 3.11 | 0.158 | 0.71 | 6.54 | 7.09 | 9.27 |
| | Vancouver | 502 | 31.2 | 1.76 | 0.090 | 0.40 | 3.71 | 4.01 | 5.25 |
| | Total | 5 420 | 337.6 | 19.02 | 0.967 | 4.33 | 40.03 | 43.36 | 56.7 |
| Landing | Cariboo | 37 | 2.3 | 0.13 | 0.007 | 0.03 | 0.09 | 0.09 | 0.14 |
| | Kamloops | 25 | 1.5 | 0.09 | 0.004 | 0.02 | 0.06 | 0.06 | 0.09 |
| | Nelson | 8 | 0.5 | 0.03 | 0.001 | 0.01 | 0.02 | 0.02 | 0.03 |
| | Pr. George | 61 | 3.8 | 0.21 | 0.011 | 0.05 | 0.15 | 0.15 | 0.22 |
| | Pr. Rupert | 6 | 0.4 | 0.02 | 0.001 | 0.01 | 0.02 | 0.02 | 0.02 |
| | Vancouver | 21 | 1.3 | 0.08 | 0.004 | 0.02 | 0.05 | 0.05 | 0.08 |
| | Total | 158 | 9.8 | 0.56 | 0.028 | 0.14 | 0.39 | 0.39 | 0.58 |
| Spot | Cariboo | 347 | 21.5 | 1.22 | 0.062 | 0.28 | 0.85 | 0.85 | 1.28 |
| | Kamloops | 474 | 29.5 | 1.66 | 0.085 | 0.38 | 1.17 | 1.17 | 1.75 |
| | Nelson | 361 | 22.5 | 1.27 | 0.064 | 0.29 | 0.89 | 0.89 | 1.33 |
| | Pr. George | 703 | 43.7 | 2.47 | 0.125 | 0.56 | 1.73 | 1.73 | 2.60 |
| | Pr. Rupert | 164 | 10.2 | 0.58 | 0.029 | 0.13 | 0.40 | 0.40 | 0.61 |
| | Vancouver | 104 | 6.5 | 0.37 | 0.019 | 0.08 | 0.26 | 0.26 | 0.38 |
| | Total | 2 153 | 133.9 | 7.57 | 0.384 | 1.72 | 5.3 | 5.3 | 7.95 |
| Wildlife/ range | Cariboo | 14 | 0.9 | 0.05 | 0.003 | 0.01 | 0.11 | 0.12 | 0.15 |
| | Kamloops | 33 | 2.1 | 0.12 | 0.006 | 0.03 | 0.25 | 0.27 | 0.35 |
| | Nelson | 121 | 7.5 | 0.42 | 0.022 | 0.10 | 0.89 | 0.97 | 1.26 |
| | Pr. George | 2 556 | 158.9 | 8.97 | 0.456 | 2.05 | 18.9 | 20.45 | 26.74 |
| | Pr. Rupert | 1 077 | 66.9 | 3.78 | 0.192 | 0.86 | 7.95 | 8.61 | 11.26 |
| | Vancouver | 0 | 0.0 | 0.00 | 0.000 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Total | 3 801 | 236.3 | 13.34 | 0.679 | 3.05 | 28.1 | 30.42 | 39.76 |
| Wildfire | Cariboo | 296 | 18.4 | 1.04 | 0.053 | 0.24 | 2.19 | 2.37 | 3.10 |
| | Kamloops | 157 | 9.8 | 0.55 | 0.028 | 0.13 | 1.16 | 1.26 | 1.65 |
| | Nelson | 518 | 32.2 | 1.82 | 0.092 | 0.42 | 3.83 | 4.14 | 5.42 |
| | Pr. George | 4 520 | 281.0 | 15.86 | 0.807 | 3.62 | 33.38 | 36.16 | 47.29 |
| | Pr. Rupert | 2 921 | 181.6 | 10.25 | 0.521 | 2.34 | 21.57 | 23.37 | 30.56 |
| | Vancouver | 686 | 42.6 | 2.41 | 0.122 | 0.55 | 5.07 | 5.49 | 7.18 |
| | Total | 9 098 | 565.6 | 31.93 | 1.623 | 7.3 | 67.2 | 72.79 | 95.2 |
| Total | | 20 630 | 1 283.2 | 72.42 | 3.681 | 16.54 | 141.02 | 152.26 | 200.19 |