FINAL REPORT

WILDFIRE EMISSIONS STUDY, GREAT LAKES REGION

PREPARED FOR:

LAKE MICHIGAN AIR DIRECTORS CONSORTIUM

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STUDY PERIOD: MAY-SEPT., 2002

INTRODUCTION & BACKGROUND

A contract was entered into between the Lake Michigan Air Directors Consortium ["LADCO"], and James Cook in late May, 2002; the general purpose of the contract was to produce an estimate of the emissions produced by the combustion of wildland fuels.

LADCO, the funding agency, was interested in obtaining an estimate of the amount of 6 specific compounds (often referred to as 'by-products' in the fire management literature) by location and on a daily basis for the upper Midwest region. For the purpose of this study, the region of interest was defined as Minnesota, Wisconsin and Upper Peninsula of Michigan. The need/desire for these data is to enable an evaluation of relative role/importance that wildland fuel combustion is having, and may have, on the total amount of emissions in the atmosphere around the Great Lakes. It was agreed that this work would be viewed as a "pilot study", in as much as no new research was expected. Rather the emission estimates were generated using existing data in the literature, combined with databases on fire size, date and location available from various land management agencies.

OBJECTIVES

In order to clarify for the reader what the expected outcomes were, I organize the "Deliverables", as specified in two letters from Mike Koerber, Exec. Dir., dated 5/16/02 and 5/30/02, into a primary and secondary group.

PRIMARY:

1. Emission estimates, by date & location for 2001
2. Emission factors (EF's) for: particulate matter, reactive organic gases, oxides of nitrogen, sulfur dioxide, ammonia and carbon monoxide
3. Evaluation of fire size as estimated and reported by land management agencies, using as much as possible the fires that occurred in 2002

SECONDARY:

1. Preliminary assessment of fraction of fuel burned
2. Fuel types involved in region
3. Plume rise parameters
4. References for source data

METHODOLOGIES

A. DATABASES

Databases of wildfire occurrence in 2001 were obtained from the Dept. of Natural Resources of each state; this constituted the majority [but not all] wildfires in the region. Wildfire numbers were also obtained from Region 9 office of the Forest Service for the 5 national forests within the region of interest, and from the regional office of the Bureau of Indian Affairs (BIA) in Ft. Snelling, MN. The data from the BIA differ from all other data gathered and reported in that their data was for the year 2000; it was necessary to use the prior year because their staff was unable to extract the data for 2001. Contact information for all sources of wildfire and prescribed fire information is provided in Appendix A.

In order to evaluate the contribution of prescribed burning to emission loads in the atmosphere, I gathered data on this class of fires from:

1. U.S. Fish & Wildlife Service (regional office, Ft. Snelling, MN)
2. Bur. Of Indian Affairs
3. The Nature Conservancy
4. Clark Forestry, Baraboo WI
5. UWSP Fire Crew, Stevens Point WI

An important limitation to the use of these data was the variation in information reported. This included such information as location (generally it was a legal description, some provided lat/long. and two of the sources on prescribed fire only gave a county) and fuel type. This latter variable is especially important and no two data sources reported this the same way.

B. EMISSION FACTORS & EMISSION ESTIMATION

The majority of EF's used were taken from Battye and Battye (2002). I also looked at articles by Yokelson et al. (1999), Ward and Hardy (1991) and Hardy et al. (1996) to see if more appropriate EF's might exist. Without exception, I did not find a single study conducted in the 3-state region that derived an EF for even one of the 6 compounds of interest. A little work done in Ontario Cananda and in Alaska included a few of the species of the Great Lakes region, and these were used whenever possible. The study from N. Carolina (Yokelson et al. 1999) was conducted in a pine/hardwood mixed forest, which has a close analog in the Upper Midweest; therefore, their values were incorporated for fuel types that match closely. The EF's used for each fuel type and size are given in Appendix B. Included with each table is a list of assumptions made to assign values.

The level of specificity of the EF's varied considerably among compounds. For example, for some an EF is available for grass fuels, for others (such as 10 micron particulate) it is not. Thus, it was often necessary to extrapolate from one fuel type to another, or from a value derived out West. This undoubtedly has introduced some error into the final estimates but neither the magnitude nor the direction [high vs. low] can be determined with existing data.

In my discussions with other research scientists, I learned of a study done in Minnesota that will soon provide the first regional estimate of some EF's. A study directed by Wei-min Hao of the Rocky Mt. Station, USFS will be published in 2003. Dr. Hao has derived EF's for particulate matter (PM), carbon monoxide and trace gases for a grassland, an oak forest and a red pine forest. He did not estimate oxides of nitrogen (NOx) or sulfur (SOx), however (pers. comm., September 2002) .

The approach taken to calculate the emissions from each wild/prescribed fire was (Battye and Battye 2002, pg. 4):

(1) Fuel consumption = Area burned (ac.) x Fuel load x Fraction Burned
(2) Emission of 'X' = Fuel consumed x Emission factor

When the data warranted, the fuel load and fraction burned was broken down by fuel type (grass vs. litter vs. woody vs. live fuel) and fuel size (woody fuels only – by the standard time lag fuel classes: 1, 10-, 100- and 1000-hr).

C. FIRE SIZE ASSESSMENT

The student field crews visited 42 fires; they determined the size of each by taking GPS readings along the perimeter and then using ArcView to calculate the area within the perimeter.

D. FUEL LOAD & CONSUMPTION ESTIMATION

The field crews were instructed to conduct a "down-n-dead' [which means woody] fuel inventory if the size of the burned area was between 10 and 100 acres, and if it had a "significant" amount of woody species present. The very large fires were not inventoried because we would have had to devote an unacceptably large proportion of time to get an accurate load estimate. For the small wildfires, which make up a strong majority of fires based on numbers, making an assumption about the fuel load is less critical than for the fires over 10 acres.

We used the Forest Service derived, standard inventory technique (Brown et al. 1982) for down-n-dead fuels. The field crews were instructed to take 6 samples in the burned area and 6 in the reference area. If no reference was available, they took 10 samples in the burned area. I arrived at this sample intensity (which is a lower intensity than recommended in Brown et al., 1982) in this manner. I had each crew conduct an inventory using 6 sample points in a forest for which I had more extensive data (from a class I teach on Fire Management), and one that has a lot of variability in species and degree of canopy closure. I compared their estimates to the class estimate, which was based on 23 sample points, to determine the probable accuracy:

Crew	Total Load	Deviation from Class Estimate
1	11.7 t/ac	+ 17.3%
2	7.5 t/ac	- 24.9 %
1+2	9.6 t/ac	- 3.8%

Thus, with 12 sample points, we came within 5% of the "true" value. When sampling a burned area, the fuel load typically would be decreased by at least 40% [see Results below]. Given this, and the comparison above, our sampling intensity probably put us within ± 20% [or better] of the actual value. Therefore, for a preliminary assessment, this probably provided a suitable level of precision. Furthermore, when the crews sampled a burn area that had no reference [10 samples] we were undoubtedly more accurate -- probably within 10% of the true value.

RESULTS & IMPLICATIONS

A. TOTAL EMISSIONS & DAILY EMISSIONS

The emission estimates are provided in 4 separate data files. They have been kept separate because of the differences in amount of information, the format of that information, potential differences in wild vs. prescribed fires, and for temporal consistency [see note above about the BIA data]. These four data files are named as follows, and contain the number of fire records indicated:

I. "WI-MN-MI_emissl_SORT"	2298 records	all wildfires reported by state DNR's
II. "FED_COMBD"	119 records	all wildfires reported on national forests
III. "PRESCR"	315 records	all prescribed fires I have 'tracked' down
IV. "BIA_2000"	452 records	all fires on reservation lands **in 2000**

** IMPORTANT NOTE** In an e-mail, the BIA Fire Mngt. Officer (Sean Hart) for the region indicated that a “typical year” would include approximately 15,500 acres burned by wildfire and 9000 acres burned by prescription. Thus, the 14,669 acres in file “IV” fall well short of his ‘long term estimate’ [approximately last 10 years].

SUMMARY of EMISSIONS – TOTAL for YEAR*, ACREAGE BURNED = 53,734 acres

Datatbase	PM2.5	PM10	NOx	Carb. Monoxide	SOx	VOC	NH3
	(-------------------	1000’s kg	----------------	----------------	----------	----------	---)
State – wild	222.9	234.1	80.3	1,939.7	42.1	133.2	8.6
Fed – wild	6.2	7.6	2.3	54.4	2.1	3.4	0.4
Prescribed	477.5	346.3	215.8	2,251.6	97.0	240.3	8.8
BIA – both	580.6	750.7	267.0	5,935.4	81.6	331.7	41.5
TOTALS (in 10^6 kg)	1,287	1,339	565.4	10,181	222.8	708.6	59.3

*Data not included: 4.4 M ac burned by TNC in Minn.; 89 ac burned by TNC in Mich., and prescribed fires conducted by the USFS.

Two surprising facts emerge from this compilation; one is that prescribed fires are contributing considerably more to the total emission load than are wild fires; and two, the BIA is the single most important “player” in this scenario. Please note that there is one additional important caveat to these conclusions – 2001 was a relatively quiet year for wildfires, and thus the relative importance of prescribed vs. wild fires could vary significantly in other years.

Using the total emissions reported above and the state wildfire databases to define the time element, a tentative estimate of the daily emissions is provided. That database (number “I” above) indicates that wildfires in 2001 began on 1/1/01 and the last one occurred on 12/21/01. Using this entire time period provides one estimate of “Daily Avg. Emissions”. It seems to me that a more meaningful figure would the “Fire Season Daily Avg. Emissions”. The distinction I am making is a simple one: namely that most prescribed AND wildfires are concentrated at particular times of the year, and thus these period(s) are the times when the combustion of wildland fuels is most likely to make a truly notable contribution to the emission load in the region. These fire seasons are represented graphically in Figure 1, and in the Excel data files [WI&MI&MN-01]. Based on acreage [not load], the figure indicates that the overall [i.e., all states combined] primary period of fire activity is spring; however, there are three time periods that are worth consideration. In 2001, the summer fire season was only important in Wisconsin. Based on the acreage data, the three fire seasons in decreasing order of importance are:

I. Spring (~4/10 – 5/20) – no. of days = 40 → 63.7%
II. Fall (~ 10/10 – 11/20) – no. of days = 40 → 20.9%
III. Summer (~ 7/10 – 8/15) - no. of days = 35 → 6.6%

"Daily Average Emissions" are:

Emission Product	355-Day Basis Mean Daily Emis. (kg)	Spring Season (40-day) Mean Daily Emis. (kg)
2.5 micron particulate	3.626×10^6	20.49×10^6
10 micron particulate	3.771×10^6	21.32×10^6
Nitrogen oxides	1.593×10^6	9.004×10^6
Carbon monoxide	28.7×10^6	162.1×10^6
Sulfur oxides	0.63×10^6	3.548×10^6
Volatile organics	2.0×10^6	11.28×10^6
Ammonia	0.17×10^6	0.944×10^6

B. EVALUATION of REPORTED WILDFIRE SIZE

My overall conclusion, based on a comparison of our estimate to that of the reporting agency, is that the sizes reported by the various agencies [three DNR's and the USFS] are of suitable accuracy to use in any future calculations undertaken by LADCO, with one caveat. The one situation in which I would not recommend "blind" acceptance is for larger than average fires. As a tentative guideline, I would suggest a cut-off of no more than 150 acres.

Using all fires, the average deviation [absolute value] between estimates was 6.3 acres; when the direction of the deviation [above vs. below] is taken into consideration the mean deviation drops to 5.1 acres (see Table 1). These numbers are the 'worst case scenario' based on our data. For three of the fires, the deviation was > 40 acres, but we have good reason to believe that these differences are due to factors <u>other than</u> the abilities of field personnel (and/or ours) to estimate acreage:

> * For the "Tuesday" fire, the largest that we looked at, the overestimate by the agency was < 10%; thus in relative terms the error was not excessively large. With large fires, the perimeter often becomes more and more irregular, as was the case for this fire. I am reasonably confident that a majority of the difference was due to the fact that we closely followed the perimeter and took readings at frequent intervals, thus more closely capturing the true shape of the fire.
>
> * For the "Sawdust Lake Fire", the difference was unacceptably large. This may be due, in part, to our inability to accurately trace the perimeter because the fire occurred in May, 1999. Also, this fire jumped a road, which we did not include in our acreage estimate. A final possible factor is the fuel type. Much of this burned area was in grass or pine regeneration. These types of vegetation are going to re-grow faster, and decompose more quickly, than woody vegetation and thus make re-location more problematic; and suggest some management activity in the recent past that could have removed some evidence of the fire. Thus, these factors suggest that our estimate is low, but it is unlikely that these explain the very large [106 ac.] difference between the two.

* The third fire with a large deviation [40.4 ac.] was the "Balsam Lake Fire". This fire burned down into swampy areas on two portions of the perimeter. Fire burning through this type of soil/vegetation often leaves little evidence. This fire also had a highly irregular shape which could easily account for part of the difference. My evaluation suggests the 'true' size is closer to the agency estimate.

If we drop these three large deviations from the dataset, the average deviation plummets to 1.9 acres [absolute value basis] and 0.6 acres [accounting for over- and under-estimates]. The details on each fire and the calculation of these deviations is provided in the file "Master Table".

Based on conversations with DNR staff in Wisc. and Minn., the accuracy of their estimates should increase in the future as more-and-more field staff use GPS/GIS to generate their acreage estimates.

C. FUEL LOADING & FUEL CONSUMPTION ESTIMATION

This protocol led to 21 woody fuel and 2 grass fuel estimates (see Table 2). Of the 21 sites with woody fuels, four did not have a suitable reference [=unburned] stand nearby. Thus, we were able to generate 17 pairs of estimates with which to evaluate this method of estimating fuel consumption. Among the 17 sites, we found:

1) 5 sites in which the burn estimate exceeded the reference,
2) 2 sites in which the two estimate were essentially (+ 0.5 tons) the same, and
3) 10 pairs that provided "useable" estimates of fuel consumption.

For the 10 'reliable' estimates, the average amount of fuel combusted equals 4.9 tons/ac. The average fuel load in the reference areas was 10.3 tons/ac. These data indicate that, on average, 48.5% of the woody fuel was burned up; the range of estimates was 21-79%. In order to check the accuracy of this value [48.5%], I compare our estimate to others reported in the literature.

For an old-growth forest in the Pacific Northwest, the 'Percent Consumed' for different components was a) understory plants - 75%, b) snags and logs - 30%, and c) forest floor - 80% (Edmonds et al. 2000). A study of two fires (one wild, one prescribed) in North Carolina reported an overall average of 'Percent Consumed' of 61-62% (Yokelson et al. 1999). In Southwestern ponderosa pine into which fire was re-introduced, the overall average fuel reduction was 65% in one location and 43 % in another (Sackett 1980). Based on three separate studies of western conifers, each with multiple burns, the average fuel reductions were: 56% for litter, 52% in the small woody fuels, and 40% for the "large" [greater than 1" diameter] woody fuels (Agee et al. 1978, Sackett 1980, Harrington 1981. The number of variables that would, and do, influence these types of fire impacts, is quite extensive, and thus a 'study-to-study' comparison is usually not warranted. This is why I have concentrated on averages from several studies and overall fuel reductions. I have also focused on low-to-moderate intensity surface fires because this represents the vast majority of wildfires in this region. And this aspect of the situation would explain why the average consumption from the N. Carolina fires was higher – based on the descriptions in the text, these fires were of a higher intensity. Given these caveats, we can conclude that our estimate is clearly within the 'reasonable range" and has an acceptable level of accuracy for a preliminary study.

Though we could only use 58.8% (10/17) of the pairs to estimate fuel combustion, I believe that this method is viable and can be used as an ‘after the fact’ way to estimate the amount of fuel actually burned up. To increase the percent of times that it would yield a reasonably accurate estimate, you should:

1) minimize the time between date of burn and date of inventory,
2) make careful selection of the reference area by doing an extensive “walk through” of both areas before deciding the suitability of the reference,
3) only using it for fires that are no larger than 70-100 acres and
4) check available records and/or talk to local land managers to find out if any strong wind storms, insect problems or harvesting has occurred since the fire. If any of these events occurred, this method is probably inappropriate.

Our estimates of fuel loading are quite similar to those reported in Ottmar and Vihnanek (1999) for the various pine fuel types, but higher than those used in the ‘BEHAVE’ fuel prediction model. This is relevant because some agencies report the fuel complex in which a fire occurred by selecting the ‘BEHAVE’ fuel model that matches best. This is additional, though indirect, corroboration of our fuel consumption estimates. Our estimates also match reasonably well with the built-in fuel loadings in the model ‘FOFEM’ [First Order Fire Effects Model, Reinhardt et al. 1997].

MAJOR INFORMATIONAL NEEDS

It is quite obvious that we (the resource professional and research scientists involved in land management) could do a much better job of wildfire tracking, reporting and providing information needed by organizations such as LADCO. Here are the important and obvious needs and possible improvements:

(1) Derive emission factors for all compounds, for each major fuel type, in the Upper Midwest – a few will be available this year[1] (see page 3) [NOTE, HOWEVER: a few of the species we have were included in studies done in Ontario and Alaska, and more of the genera were included in studies done in the Intermountain West and the South].
(2) Obtain more species-specific and size class-specific emission factors for SOx; this is clearly the most poorly studied compound.
(3) Standardize the wildfire AND prescribed fire information reported– there is at least one relatively important difference among each possible pair of agencies. The most important item I see in this regard is fuel models.
(4) Standardize the wildfire AND prescribed fire information software/system used to track and record the information.
(5) Derive fuel model descriptions and load estimates for aspen, northern hardwoods, regenerating forests, tree/grass mixtures, pine/oak mixtures and other non-represented fuel complexes.
(6) Determine fuel consumption values for a) forest litter and b) grassy fuels. The data I see in the literature suggests that a 90% consumption level for fine, non-woody fuels is too high.

[1] A researcher out of the Rocky Mt. Station [Wei-min Hao, 406-329-4838] will be reporting emission factors for carbon monoxide, particulate and trace gases.

LITERATURE CITED

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Yokelson, R.J., J.G. Goode, D.E. Ward, R.A. Susott, R.E. Babbitt, D.D. Wade, I. Bertschi, D.W.T. Griffith and W.M. Hao. 1999. Emissions of formaldehyde, acetic acid, methanol and other trace gases from biomass fires in North Carolina measured by airborne Fourier transform infared spectroscopy. Journal Geophysical Research 104(D23):109-130.

APPENDIX A. DATA SOURCES USED IN THIS ANALYSIS

1. Bureau of Indian Affairs, Ft. Snelling MN.
   Sean Hart, mail364925@pop.net
   Carl Hardzinski 612-713-4400, ext. 1144

2. Clark Forestry, Baraboo WI
   Joel Green, jgreen@clarkforestry.com

3. The Nature Conservancy, Madison WI
   Steve Richter, srichter@tnc.org

4. Applied Ecological Services, Brodhead WI
   Steve Apfelbaum
   appliedeco@brodnet.com, 608-897-8641

5. UWSP Fire Crew, Stevens Point WI
   Johnny Micheel, jmich544@uwsp.edu

6. U.S. Fish & Wildlife Service, Ft. Snelling MN
   Brian McManus, Brian_McManus@fws.gov, 612-713-5366

7. Minnesota DNR, Grand Rapids MN
   Barb Meyer, barb.meyer@dnr.state.mn.us, 218-327-4570

8. Wisconsin DNR, Madison WI
   Gary Steffen, Gary.Steffen@dnr.state.wi.us, 608-266-2195

9. U.S. Forest Service (all national forests)
   Janis Hancock, Milwaukee WI, jhancock@fs.fed.us, 414-297-3348

10. Michigan DNR, Lansing MI
    Donald Johnson, johnsod4@michigan.gov, 517-335-3348

APPENDIX B. EMISSION FACTORS & ASSUMPTIONS for ASSIGNING VALUES

I. PARTICULATE MATTER EF's: (See Table 22 in Battye & Battye, 2002)

	PM2.5	PM10	SLASH
Litter	8	10	SAME
1, 10-hr	12	16	9, 13
100+hr	18	24	12,17
Shrub, live	22	28	N/A

Assumptions & Decisions:

1. No consistent basis for assigning different values to conifer vs. broadleaved species.
2. Variation among size classes is due primarily to combustion efficiency (CE).
3. The EF for Dormant Brush/Hwd. Slash is closest to "slash"
4. Grass EF set equal to Litter.
5. For these EF's and all others, the values for slash are taken as 'Broadcast burned', not 'Pile-and-burn'.

II. NITROGEN OXIDE EF's: (See Table 26 in Battye & Battye, 2002)

FUEL MODEL	Fines	1+10-hr	Shrub/live	100-hr+
A1, A2, A3, B1	7	0	0	0
A4	6.1	5	13	5
C1	10	0.8	0	0.8
C2, C3, F1	5.4	4.5	13	4.5
C4	7.7	2.6	0	2.6
D1, D2, D3	5.4	3.1	0	3.1
E1, E2, E3	7	0.8	13	0.8
F2, F4, F5, F6	10	0.8	13	0.8
F3	5	4	0	4

Assumptions & Decisions:

1. Douglas-fir & J. pine/spruce values used for F3 (spruce-fir)
2. For models with trees and grass, EF = average of two values for 'fines'
3. Due to lack of data by size class, the same value had to used for 1-hr through 1000-hr size classes.
4. EF for Hwd. Litter assumed higher than for conifer due to high correlation between Nox-Ef and %nitrogen concentration.
5. For all 'generic' conifer models in WI and MN, the EF was calculated as the average for "pine" and Jack pine [= → 4.5 lb/t].
6. Weighted value for C2 is 6.1, for C3 it is 4.8

III. CARBON MONOXIDE EF's: (See Tables 19, 20 in Battye & Battye, 2002)

FUEL MODEL	Fines	1+10-hr	Shrub/live	100-hr+
A1, A2, A3, B1	52.4	0	0	0
A4	52.4	111.4	249.2	205.8
C1	71.4	151.8	0	280.4
C2, C3, F1, F3	52.4	111.4	249.2	205.8
C4	61.9	131.6	0	243.1

D1, D2, D3	75.4	172.0	0	205.8
E1, E2, E3	71.4	151.8	249.2	280.4
F2, F4, F5, F6	71.4	151.8	338.9	280.4

Assumptions & Decisions:

1. The values for C1 were taken from Table 19 but adjusted upward by 136% based on differences between conifers and hardwoods as indicated in Table 20.
2. For the slash models [D1-3], I assumed that all fines burned as flaming combustion, one-half was flaming for the '1+10-hr' category, and that the '100-hr +' was all smoldering.
3. For the Models E1-E3, assumed that hardwoods dominated
4. For F2,F4,F5 & F6, the values were adjusted for hardwoods, as done for C1.
5. For fuel models which a breakdown by fuel size did not seem warranted, but included woody fuels, an EF of 150.8 was used. This is a weighted average of the conifer values for the "fines" and "shrub/live fuels" [(52.4 + 249.2)/2]

IV. SULFUR OXIDES EF's: (See Table 29 in Battye & Battye, 2002)

FUEL MODEL	Fines	1+10-hr	Shrub/live	100-hr+
A1, A2, A3, B1	2.8	0	0	0
A4	2.8	2.8	2.8	0.86
C1	2.8	2.8	0	0.86
C2, C3, F1, F3	2.8	2.8	2.8	0.86
C4	2.8	2.8	0	0.86
D1, D2, D3	2.8	2.8	0	0.86
E1, E2, E3	2.8	2.8	2.8	0.86
F2, F4, F5, F6	2.8	2.8	2.8	0.86

Assumptions & Decisions:

1. Value for 'Shrub/live' taken from value for sagebrush
2. Composite, weighted average values used:
   A. Federal file:
      i. A2: 2.8
      ii. C2: 1.98
      iii. C3: 1.83
   B. BIA2000 file:
      i. A4: 2.55
      ii. F1: 2.08

V. VOLATILE ORGANIC COMPOUND EF's: (See Yokelson et al. 1999, Table 28 in Battye & Battye, 2002)

FUEL MODEL	Fines	1+10-hr	Shrub/live	100-hr+
A1, A2, A3, B1	6.4	0	0	0
A4	5.0	12.8	25	5.8
C1	2.6	19.8	0	9.0
C2, C3	5.0	12.8	0/25	5.8
C4	3.8	16.3	0	7.4

D1, D2, D3	5.0	5.8	0	5.8
E1, E2, E3	2.6	19.8	25	9.0
F1, F3	5.0	12.8	25	5.8
F2, F4, F5, F6	2.6	19.8	2.8	9.0

WEIGHTED COMPOSITE VALUES

1. A4, C2	9.98
2. C1	8.43
3. C3	6.96
4. E1, E2	13.97
5. F1, F3	8.48
6. F2,F4,F6	13.97

Assumptions & Decisions:

1. Black spruce value is the best representative value for spruce, fir in Lakes States.
2. Broadcast slash value is best available for 100-hr+ category
3. Pine/oak value for Fire #2 (Yokelson et al. 1999) is best available value for woody component of hardwood fuel models
4. Ponderosa pine value is best available for pines in Lake States
5. ‘Black spruce + shrub’ is best available for shrub/live category
6. Sagebrush is best available for hardwood litter
7. Hardwood 100-hr+ value calculated as proportional reduction of the 1+h0-hr value, using pine as a guide [5.8/12.8 = 45.3%]

VI. AMMONIUM EF’s: (See Table 27 in Battye & Battye, 2002)

FUEL MODEL	Fines	1+10-hr	Shrub/live	100-hr+
A1, A2, A3,	0.06	0	0	0
A4, C2, C3, F1,F3	0.63	1.12	1.54	1.12
B1	0.54	0	0	0
C1	0.2	0.2	0	1.54
C4	0.41	0.66	0	1.33
D1, D2, D3	0.2	1.14	0	1.14
E1-3, F2,F4,F5,F6	0.2	0.2	1.54	1.54

WEIGHTED COMPOSITE VALUES

1. A4, C2, F1	1.07
2. C1	0.276
3. C3	1.01
4. E1	0.64
5. E2, E3	0.717
6. F4	1.277

APPENDIX C. FUEL MODEL SYMBOLS & SOURCES

MODEL REPORTED	MODEL USED IN CALCULATION	SOURCE
MINNESOTA		
Upland grass	A2	Photo Series, Tall Prairie #10
Lowland grass	B1	Photo Series, Tall Prairie #14
Leaf/needle litter	C4	BEHAVE #8&9, averaged
Moderate slash	D2	BEHAVE #12
Conifer regen/brush	E2	BEHAVE #5 + O.5 t “live”
WISCONSIN		
Short grass	A1	Photo Series, Tall Prairie #2
Tall grass	A3	Photo Series, Tall Prairie #12
Timber	C2	BEHAVE #10
Light logging slash	D1	BEHAVE #11
Brush	E1	BEHAVE #5
Chaparral	E3	BEHAVE #4
Heavy logging slash	D3	BEHAVE #13
Medium logging slash	D2	BEHAVE #12
Closed timber litter	C3	BEHAVE #8
Timber + grass	A4	BEHAVE #2, adjusted
MICHIGAN		
White/red/jack pine	F1	Photo Series, MP#4, adjusted
Aspen-birch	F2	FOFEM
Maple-beech-birch	F3	FOFEM
Spruce-fir	F4	Photo Series, MP#6
Oak-hickory	F5	FOFEM
Elm-ash-cottonwood	F6	no analog, used Maple-birch
Grass	A2	Photo Series, Tall Prairie #10

Table 1. Area estimation comparison and area precision determination.

WILDFIRE EMISSIONS STUDY by J. COOK, UWSP

Week	Ownership	State	Fire Name	Area Estimate (ac) Agency	Area Estimate (ac) Crew	Diff. (ac.) Crew - Agency	Absolute Diff.	Fuel Invent.	Reason Not Done	Lat./Long.
1	State	WI	Spike Buck	40	40.05	0.05	0.05	Y		46:14.3130N 91:50.3269W
1	Private	WI	Muscoda Pipeline	28.7	22.8	-5.9	5.9	Y		43, 11' 21"N 90, 28' 02"W
1	Private	WI	Mc Farlin	30.5	29.5	-1	1	Y		43, 40' 12"N 89, 44' 25"E
1	Private	WI	Mc Farland	11.4	11.5	0.1	0.1	N	rough topography/time	43,40' 18.17"N 89,43'.854" W
1	Private	WI	Fenner	10	9.2	-0.8	0.8	Y		43, 57' 12"N 89, 20' 31"E
1	Private	WI	Walter	1	0.8	-0.2	0.2	N	too small	45, 11' 07"N 89, 49' 34"E
1	Industrial/ Private	WI	Flamang	172	171.28	-0.72	0.72	N	knocked down all dead trees to replant	46, 16' 05"N 91, 41' 22"W
2	State	MN	Tuesday	450	403	-47	47	N	too big	47, 57.191"N 90, 6.302' W
2	Fedral	MN	Wolf Track	18	10.68	-7.32	7.32	Y		47, 56' 05"N 91, 27' 30"W
2	Private	WI	County B Snag	9	5.32	-3.68	3.68	N	too small	45, 45' 32"N 92, 08' 49"W
2	Public	WI	Smoking Helmet	9.6	9.2	-0.4	0.4	Y		45, 34' 47"N 92, 47' 34"W
2	Private	WI	Mell	21	20.1	-0.9	0.9	Y		46, 02' 17"N 91, 12' 17"W
2	Private	WI	Horseshoe	6	9.2	3.2	3.2	Y		46, 06' 12"N 92, 00' 15"W
2	Private	WI	Race Track	17	26.6	9.6	9.6	Y		46, 32' 49"N 90, 52' 59"W
3	Industrial/Private	WI	South Twin	8.39	7.71	-0.68	0.68	N	too small/slash fuel	46, 14' 12.7"N 90, 16' .73"W
3	Industrial/ Private	WI	North Twin	19.72	18.95	-0.77	0.77	N	slash main fuel	46, 15' 6.58"N 90,12' 54.91"W
3	State	MN	Balsam Lake	163	122.63	-40.37	40.37	Y		47, 33' 2.91"N 91, 12' 56.52" W
3	National Forest	MN	Santa Maria	5.7	3.6	-2.1	2.1	N	too small	47, 18' 38"N 93,59'15"W
3	National Forest	MN	Decker Lake	3	2.91	-0.09	0.09	N	too small	47, 38' 3"N 94,21' 00"W
3	National Forest	MN	Pike Bay Loop	55	60	5	5	Y		47, 19' 541"N 94,33' 906"
4	Industrial/Private	WI	Hwy Y Party	2.75	n/a			N		45, 34' 20.54"N 89, 47' 8.60"W
4	Private	WI	Baker Lake	1.7	1.52	-0.18	0.18	N	too small	46, 5' 21.83"N 89, 22' 44.87"W
4	National Forest	WI	Saw Dust Lake	258	152.2	-105.8	105.8	N	too big	48, 34' 53.9880" N 91, 15' 44.1540"
4	National Forest	MI	J-32	1.2	1.26	0.06	0.06	N		45, 51' 28" N 86, 53' 31"W
4	National Forest	MI	IBT	18	17.9	-0.1	0.1	Y		46, 29' 43" N 88, 46' 37"E
4	National Forest	MI	Little Aspen	7	6.8	-0.2	0.2	N	too small	46, 29' 20.5"N 88, 47' 54" E
4	National Forest	MI	Gasley Ridge	2.5	2.65	0.15	0.15	N	too small	46, 25' 10" N 88, 45' 56"
4	Private	WI	Palmer Rd.	46	39.6	-6.4	6.4	Y		45, 26' 56" 88, 02' 58"
5	Private	WI	Dresdow	22	19	-3	3	N	large majority was salvaged/disturbed	44, 17' 7.45"N 89, 15' .81" W

5	Industrial/Private	WI	County Line	31	32.7	1.7	1.7	Y		44, 15' 5.76"N 89, 45' 16.66"W
5	Industrial/Private	WI	Plum Creek	91	90.2	-0.8	0.8	Y		44, 15' 50.82"N 89, 50' 20.77"W
5	Industrial/Private	WI	Easter Monday	158	156	-2	2	Y		44, 14' 6.77"N 89, 49' 23.07"W
5	State	WI	Babcott # 66	21	18	-3	3	Y		44, 13' 47"N 90, 11' 14"W
5	Private/County	WI	30th Ave	30	29.4	-0.6	0.6	Y		43, 57' 59"N 90, 05' 59"W
5	Public	WI	# 165	32	31.1	-0.9	0.9	Y		44, 14' 32"N 89, 56' 19"W
5	Private	WI	Woodland	65	68.1	3.1	3.1	N	big portion was clearcut after burn	43, 58' 38"N 90, 11' 13"W
5	Both	WI	Koval Road	48	48.9	0.9	0.9	Y		43, 41' 08"N 89, 52' 04"W
6	County/Private	MN	Dr. B	133	n/a			Y		46, 24' 29"N 92, 30' 99" W
6	Private	MN	Belly Pan	23	n/a			N	marsh	48, 27' 36" N 93, 34' 53"W
6	Private	MN	Jaska	8.14	n/a			N	clearcut since fire	48, 10' 57" 93, 34' 6" W
6	Private	MN	Little Harriet Lake	28	29.3	1.3	1.3	Y		47, 18' 6.61"N 93, 0' 8.25"W
7	State	WI	Colburn	62	56	-6	6			44, 06' 30"N 9, 11' 23"W
					Sum Deviations -->	-215.75	266.07			
					Sum Dev. **Without** 3 large values -->	-22.58	72.9			
					Avg. Dev. -->	-0.56	1.87			
					Without 3 large values					
					Avg. Absolute Dev.	6.34				
					Including All Values					

Table 2. Post-fire and fuel load consumption estimates.

WILDFIRE EMISSIONS STUDY by J. COOK, UWSP

Week #	Fire Name	Fuel Type	Estimates (tons/ac)		Fuel Combusted	Avg. Max Grass Ht.	Estimated	FUEL
			Burn	Reference	(Ref - Burn)		Load	MODEL
1	Muscoda Pipeline	dry prairie/j.p. scrub oak	9.98	14.57	-4.59			
1	Mc Farlin	jack pine/oak	9.75	18.73	-8.98			
1	Fenner Fire	red oak/white pine/red maple	6.76	15.31	-8.55			
1	Spike Buck Fire	jack pine/bur & white oak	4.79	8.91	-4.12			
2	Wolf Track Fire	jack pine	23.24	n/a	n/a			
2	Horseshoe Fire	young jackpine/scrub oak	4.25	8.74	-4.49			
2	Race Track Fire	tall grass/aspen woodland	2.31	5.31	-3			
2	Smoking Helmet Fire	grass/aspen	4.25	4.15	+0.1			
2	Mell Fire	grass	n/a	n/a	n/a	2.41 ft.	2.5	TP11*
3	Pike Bay Loop Fire	red pine	8.28	13.57	-5.29			
4	Palmer Rd. Fire	grass	n/a	n/a	n/a	1.45 ft.	2.3	TP08
4	IBT Fire	pine plantation	15.5	14.65	+.85			
5	165 Fire	red pine plantation	10.15	3.65	+6.5			
5	Easter Monday Fire	red pine plantation/jack pine	10.79	n/a	n/a			
5	County Line Fire	red pine	2.66	2.82	(-.16)			
5	Plum Creek Fire	red pine plantation	2.37	1.07	+1.30			
5	Babcock #66	oak/aspen	7.23	10.62	-3.39			
5	30th Ave Fire	mature oak stand/scattered jack pine	5.61	7.09	-1.48			
5	Koval Road Fire	scrub oak/pine some regen	2.78	13.03	-10.25			
6	Dr. B Fire	aspen/birch	10.29	n/a	n/a			
6	Little Harriet Lake	aspen slash and regen	22.95	23.25	(-.3)			
6	Balsam Lake Fire	balsam/red pine/ white spruce	9.71	n/a	n/a			
7	Colburn Fire	oak/aspen	11.41	9.81	+1.6			

* Source = Ottmar, R and R. Vihnanek, 1999

AVG. AMOUNT CONSUMED (n=10) --> 4.9 tons/ac.

Figure 1. Time Series of Fire Acreage Burned