Atmos. Chem. Phys. Discuss., 13, C969–C981, 2013
www.atmos-chem-phys-discuss.net/13/C969/2013/

Interactive comment on "Combustion efficiency and emission factors for US wildfires" *by* S. P. Urbanski

S. Urbanski

surbanski@fs.fed.us

Received and published: 4 April 2013

Response to Referee #3

We would like to thank all three referees for their constructive comments and suggestions. The referees' comments and suggestions have greatly improved our manuscript. We truly appreciate the effort that all three referees invested in reviewing our manuscript. The original comments of referee #N are labeled RN.X and our response is labeled AN.X. We have proposed significant revisions to some sections of the manuscript. These significant revisions may respond to the comments of multiple referees and are provided as a supplement. The proposed significant revisions are labeled SR.Y and are ordered according to page and line number of the original manuscript. When one of the referee's comments has been addressed with significant

revisions to the manuscript the relevant SR.Y are referenced.

Referee #3

The manuscript presents so far unpublished high-quality aircraft measurements of CO_2, CO and CH_4 from three large wildfires and one prescribed fire in mixed conifer forests of the northwestern United States. From these measurements, the author calculates emission factors (EF) for these species and analyses the relationship between observed modified combustion efficiency (MCE) and $EFCH_4$. The author uses fuel consumption and MCE measurement data from 18 prescribed fires described in literature to statistically explore the linear relationship between the ratio of heavy fuels consumption and MCE. By combining the average MCE measured in this study with linear EF-MCE relationships found for temperate conifer-dominated forests in other studies, wildfire EF for 14 additional species are estimated. The author concludes that fuel composition is an important driver of variability in MCE and EF, and that wildfires, due to a higher fraction of large diameter fuels consumed, predominantly burn with lower MCE than prescribed fires. The author further concludes that the application of EF from prescribed fires for estimating emissions from wildfires will lead to significant underestimates of emissions typical for smoldering combustion (low MCE fires), such as $PM_{2.5}$ and NMOC. The emission characteristics of wildfires in temperate forests and the differences to prescribed burns are still poorly described in literature. The manuscript provides valuable information to improve emission inventories from these fires. The manuscript fits well into the scope of the journal and I recommend it for publication in ACP provided that it is substantially revised.

R3.1. First of all, I agree with the comments on this manuscript by the reviewers #1 and #2 that the interpretation and discussion misses a well-defined scope and clear statements on the uncertainty and transferability of the measured factors for estimating temperate wildfire emissions in general. Suggestions already made by the reviewers #1 and #2 will not be repeated here.

A3.1. We have thoroughly addressed the comments of referees #1 and #2. We have better defined the scope of our paper and clearly stated the uncertainty and transferability of the measured emission factors for estimating temperate wildfire emissions in general. Our responses to their comments and specific manuscript revisions have been provided in our responses to these referees.

R3.2. Secondly, the presentation and discussion section of the new CRDS measurement data, which I consider of key value for this paper, is much too sparse.

A3.2. We expanded the presentation and discussion of the new CRDS measurement data. Please see SR.6

R3.3. Thirdly, the structure of the manuscript is not well-arranged and needs to be improved.

A3.3. The structure of the manuscript has been rearranged following the specific comments of Referee #3 as described in our responses below and our proposed significant revisions.

R3.4. A fourth aspect addressing the quality of writing: In my opinion, it must not be the task of the reviewers assigned by ACPD (which mostly – so also me –are not native English speakers) to correct for the numerous punctuation and grammatical errors contained in this manuscript (some examples: P41L21: "Frequent, in-flight, calibrations" (superfluous commas); P42L18: "throughout the perimeter interior" (correct: perimeter's interior); P43L9: "emission factors for the each compound" (correct: emission factors for each compound); P43L12: "while, the second approach (Eq. 2) used" (superfluous comma); P43L22: "therefore our neglect other carbon-containing species" (correct: our neglect of other); P57L17: "and in the case of one fire, a previous burn." (missing comma before "in case"); P5712: "An examination of results [. . .] show a clear trend" (correct: shows); P57L24: "This observation suggests the comparatively low MCE [...] from" (missing "that" after "suggests"). Please ensure that native speaking internal reviewer (e.g. one of your colleagues at your institute) reads carefully

through your manuscript before resubmitting

A3.4. The revised manuscript has been thoroughly reviewed for typos, punctuation, and grammatical errors.

1 General Aspects

R3.5. The abstract is too lengthy containing detailed introductory remarks and a detailed presentation/interpretation of results. Please restrict the abstract to the key information. Please add a sentence defining the aim of the study.

A3.5. The abstract has been revised. Please see SR.1

R3.6. Two key hypotheses of this paper are that emission characteristics of prescribed burns differ from those of wildfires in temperate conifer-dominated forests of western US and that prescribed fires, due to the lower fraction of large diameter fuels consumed, are expected to burn with more flaming combustion than wildfires and therefore have lower EF values for species characteristic for smoldering combustions, such as CH4. It is confusing that the hypotheses are somewhat subverted by the measurement results, namely in that the measured emission characteristics of the prescribed fire shows no distinct differences to the three wildfires. In fact, the prescribed fire exhibits the lowest MCE and the highest EFCH4 of all nine fire-day averages in Tab. 2, contradicting the second hypothesis postulated in this paper. The author argues that the prescribed fire was burning during the wildfire season and can therefore be treated as wildfire. This implies that only prescribed fires burning outside the wildfire season exhibit emission characteristics different to wildfires. Wouldn't it then make sense to rather discriminate between temperate fires during and outside the wildfire season? The author compares and discusses the wildfire result to measurements of prescribed temperate fires without addressing their timing. It is very important that these aspects are clarified in detail.

A3.6. We agree with the referee and we have revised the paper carefully to differentiate between forest fires (wildfires and prescribed) that occur during the wildfire season and prescribed burning that occurs outside the wildfire season. We have revised the Introduction to describe the timing of the western US wildfire season and describe typical prescribed fire practices. It was our intent that prescribed burning during the wildfire season was implicitly included as 'wildfires' in our paper. This was not clear and the manuscript has been revised accordingly. We note that in the western US prescribed burning is very minor contributor to forest burned area during the wildfire season. The referee's concern has been addressed by revisions in several parts of the manuscript. Manuscript revisions addressing comment R3.6 are: SR.2, SR.3

R3.7. In the beginning of the introduction, a clear definition of both fire type categories (prescribed fires and wildfires) is missing. Please explain in more detail the differences between them, e.g. in terms of temporal and spatial patterns (e.g. what a fraction occurs during the wildfire season), fire size, fuel and combustion characteristics (e.g. loading, arrangement and moisture of fuels, fire intensity). The emission factors presented in this study are of high value for those working on establishing regional to global scale biomass burning inventories. Please provide some guidance on how to discriminate between wildfires and prescribed temperate fires on these spatial scales and how to best apply the emission factors derived in this study

A3.7. We have revised the Introduction to provide a clear definition of wildfires and prescribed fires. The revision also describes the temporal and spatial extent of the western US wildfire season. We provide greater detail on the differences between wildfires and prescribed fires in terms of spatial and temporal patterns. The Discussion and Conclusion have been revised to provide guidance on the application of the emission factors in this paper for emission modeling and inventory development. Manuscript revisions addressing comment R3.7 are: SR.2, SR.3

R3.8. Principally, I find the structure of this manuscript hard to read as the individual sections (introduction, methods, results/discussion) are somewhat mixed up. Please put some effort to improve the clearness of the manuscript.

A3.8. We have invested significant effort in reorganizing the manuscript structure. The changes are described in our responses to the referee's detailed comments below.

R3.9. P36L15: Please consider rephrasing (e.g. "the individual contribution of wildfires or prescribed fires") since the contribution of prescribed fires to O3 related air quality degradation is as difficult to quantify as of wildfires.

A3.9. P36 L15 has been revised to: "Because O3 is a secondary pollutant resulting from complex chemistry, quantifying the individual contribution of wildfires or prescribed fires to O3 formation is difficult."

R3.10. P38 L27: Please explain the reason why you introduced fire-days (sample number for statistics).

A3.10. Text in Sect 3.1 which describes our reason for introducing fire-days has been moved to this location. P38 L27 has been revised to: "The Big Salmon Lake Fire and the Saddle Complex were sampled on multiple days and we have treated these sampling days as separate fires, identifying each as a 'fire-day', resulting in a total of 9 fire-day emission datasets. We believe this treatment is justified given the complex terrain, heterogeneous fuels, and the inter-day variability in observed fire behavior (see Table S1). Furthermore, one day is an appropriate temporal scale for atmospheric chemical modeling applications since most biomass burning emission inventories provide estimates on a daily basis, from which models then create an hourly profile based on assumptions about diurnal fire behavior cycles." Note: We have revised Table 1 and added a supplemental table, Table S1. The fire behavior observations are included in Table S1.

R3.11. P39/40 (Methodology: Site descriptions): Please provide detailed statistics what fuels burned in each site (fraction grassland, tree species, including a best-guess estimate of the fraction of large diameter fuels burned), preferably in a supplementary table or chart. Please integrate the specific fire weather/fuel moisture situation at each site (Table 1) into the text. How did the sites differ in terms of all these parameters?

Please also provide approximate coordinates for each site. To improve the structure of the paper, please move the description of the Saddle Complex Fire (P45L13-21, including Fig. 1) into this section.

A3.11. We have revised Table 1 to have the following columns: Fire, Location (e.g. Bob Marshall Wilderness, Montana, US), Latitude, Longitude, and Vegetation Involved as Percent of Burned Area. The methods used to estimate the vegetation cover involved are described in a Supplement added to the revised manuscript. We have added Table S1 in the Supplement, which provides the daily fire (size, growth, and observed behavior) and fuel moisture information from the original Table 1 along with best-guess estimates of the fraction of fuel consumption that may have been CWD and Duff (HFF). The methods used to estimate fuel consumption are described in the Supplement. We have also integrated the fire weather / fuel moisture information into the text as part of a narrative that describes how these parameters varied between sites and over time. The description of the Saddle Complex Fire (P45L13-21) and Fig. 1 have been moved into Sect. 2.1 Site descriptions. Manuscript revisions addressing comment R3.11 are: SR.4

R3.12. P41 L4: Since the results of the H2O measurements are not presented or discussed in this study, there is no point of mentioning them.

A3.12. The mention of H2O has been removed from the text.

R3.13. P42/43 (Methodology: Airborne sampling): Please explain in detail how you defined a sample run. Please also add more information on the airborne sampling procedure and conditions for each fire/fire-day (wind conditions, plume height, transect characteristics). To improve the structure of the paper, please move the description of the sampling of smoke from the Saddle Complex Fire (P45L21-P55L2) into this section.

A3.13. We have revised Sect. 2.3 Airborne sampling to explain in detail our definition of a sample run. Sect. 2.3 has also been revised to provide more information on the airborne sampling procedures. We have moved the description of the sampling of

smoke from the Saddle Complex Fire (P45L21-P55L2) into this section. The transect locations are provided in Table 2 and our revision of the airborne smoke sampling section describes the two transect types used. Information on wind conditions have been included in our new Table S1. Manuscript revisions addressing comment R3.13 are: SR.5

R3.14. P43L7: Please specify if EMR refers to the volume or mass mixing ratio.

A3.14. The text has been revised to specify “volume” mixing ratio: “For each smoke sample the excess volume mixing ratio (EMR) of compound X, ΔX, was calculated for each 2 s data point by subtracting the average background (Xbackground) for that sample run (ΔX = Xsmoke – Xbackground).”

R3.15. P44L4 (Equation 2): The differences in the results using Equation 2 compared to Equation 1 are addressed in a single sentence only (P46L9/10). In my opinion, there is no point of presenting Equation 2 without presenting the individual results. Please consider showing the individual results of both equations or removing Equation 2 and modifying P46L9/10 into e.g. “The fire-day average EF (Eq. 1) agreed within 10% with the EF that were calculated from zero-forced linear regression of the emission ratios of the 2 s data points”.

A3.15. We have removed Eq. 2 and references to Eq. 2. We have revised P46 L9/10 as: “The fire-day average EF (Eq. 1) agreed within 10% with the EF that were calculated from zero-forced linear regression of the emission ratios of the 2 s data points.”

R3.16. P44L5-P55L10: This section primarily contains a more general reasoning on the differences between flaming and smoldering emission characteristics and of the usability of MCE to differentiate between both combustion modes. It should thus be partly moved to the introduction section.

A3.16. We removed the text at P44L5 – P44L14. This text has been folded into the revised Introduction (SR.2).

R3.17. P45/46 (Results and discussion: Emission measurements): Please describe and discuss the results of the emission measurements individually for each fire/fire-day and in comparison to each other. Please also incorporate the individual fire characteristics (Tab. 1) into the discussion. Please also address the observed variability in the measurement data, e.g. EFCO spans from 89 to 173 g kg-1. How do you explain this large variability?

A3.17. We have significantly revised Sect. 3.1 Emission Measurements to describe and discuss the results of the emission measurements individually for each fire/fire-day and in comparison to each other. The observed fire behavior and characteristics (which have been moved to Table S1) have been incorporated into the discussion. The variability in the measurement data has been addressed. Manuscript revisions addressing comment R3.17 are: SR.6 We note that most previous published studies of in-situ wildfire / prescribed emission measurements report only fire average (or plume average) EF and MCE and do not provide detailed reporting on the variability of individual samples as we do in this study. Some studies do not even provide uncertainty estimates or measures of variability of fire average EF they report. Yokelson et al. (1999) used an airborne FTIR to measure emissions from prescribed fires in North Carolina. They provide detailed emission measurements on a per sample basis for a prescribed burn conducted in mature pine forest (their Table 1). Interestingly, when we apply our Eq. 1 to each sample in their Table 1 we find the sample EFCO vary between 53.2 and 184.2. Yokelson et al. (1999) J. Geophys. Res. 104, 30,109-30,125.

R3.18. P46L3: According to Tab.2, SC2402 has a smaller number of individual measurement points (namely n=55) than actually shown in Fig. 2 (namely n=63). Please explain this difference. More principally: How robust is your analysis in respect to your definition of a sample run?

A3.18. First, we respond to the comment regarding Fig. 2 and Table 2. In Table 2

the number of individual measurement points is the number of measurement points in the smoke plume. In Fig. 2 several background measurement points (the first 6 and the last 2) have been included to highlight the enhancement above background. We have revised Fig. 2 by adding vertical dotted lines that mark the start and end of the smoke plume. Fig. 2 caption has been revised as: "Figure 2. CRDS measurements of CO2, CH4, and CO for a smoke sample run on the Saddle Complex on August 24, 2011. The horizontal dashed line in each panel shows the background mixing ratios measured upwind of the fire on approach for the smoke sample. The vertical dotted lines mark the start and end of the plume." Here we respond to the referee's question regarding how robust our analysis is with respect to our definition of a sample run. Our definition of sample run, which has been described in detail in the manuscript revisions in response to R3.13, is fairly simple. A sample run is a level altitude flight segment that begins in smoke free air, transverses the smoke plume, and then exits the smoke plume into smoke free air. The plume boundaries are identified by the CO mixing ratio. The fires we studied were in remote areas and the CO levels in smoke free air were usually around 0.10 ppmv, while the average CO level inside the plume was 0.88 ppmv. We used a CO threshold of CObackground + 0.030 ppmv to identify the start and end of the plume, where 0.030 ppmv is the typical in-flight precision of the CRDS CO measurement defined as the 14 s standard deviation while measuring a calibration standard. Due to the heterogeneity of the smoke plumes there were occasional measurement points that fell below this threshold during long sample runs. Such points accounted for less than 5% of the data points and their inclusion had a minimal impact on the sample average EF for all but a few samples. There were 5 samples where EFCO changed between $\pm$3% and 6 samples where the EFCH4 changed between -3% and +6%. The impact on EFCO2 and the remaining EFCO and EFCH4 was negligible. The fire-day average EF and MCE were unchanged. One could argue for a higher threshold for plume identification, e.g. 2 times the precision of the measurement (CObackground + 0.060 ppmv). We recalculated the sample EF using this threshold and the results were similar. We found there were 5 samples where EFCO changed between -6% and +4% and 4 samples where the EFCH4 changed between -2% and +3%. The impact on EFCO2 and the remaining EFCO and EFCH4 was negligible. The fire-day average EF and MCE were unchanged. A related issue is the treatment of the sample runs to derive a fire-day average EF. We used a simple straight average of the sample EF to derive fire-day average EF. However, another approach would to weight the samples by the number of data points. We recalculated the fire-day average EF by applying Eq. 1 to all 2 s data points for each fire-day, effectively reducing each fire-day to a single sample. We found the fire-day EF determined in this manner typically differed from the values in Table 2 by only a few percent.

R3.19. P50L4-P51L10: This section provides information on the methodology used to derive EF for species not measured in this study. Please consider moving this section to the methodology section.

A3.19. This section has been significantly revised in response to comments 5 and 7 of referee #1. Please see SR.8 for details.

R3.20. P53-P56: This is a nice literature analysis on the relation between CWD, fuel moisture and MCE (or EF). While it is well readable, it is a bit lengthy – please try to condense this section.

A3.20. We were able to condense this section by several lines. Please see SR.11 for details.

R3.21. P69 (Table 1): The line arrangement in the table is not correct. Is it typographical error that the daily burned area growth rate of the Hammer Creek fire on Aug. 22 is 0 ha? The description of the fire activity is much too casual and needs some refinement.

A3.21. We have revised Table 1 and added Table S1 described above (A3.11). The line arrangement of the revised tables has been corrected. The estimated daily growth rate of the Hammer Creek Fire on August 22 is 0 ha, it is not a typo. The description

of the fire activity has been moved from Table 1 to Table S1. The description of the fire behavior was reproduced nearly verbatim from the ICS-209 reports. We have refined the description in the revised Table S1.

R3.22. P70-71 (Table 2): In this table, you provide the study average of the individual fireday averages and the fire day averages calculated from the average of the sampling run averages. I would also like to see the summary statistics of the individual 2s data. Please display the study average EFCO value with one decimal number.

A3.22. We modified Table 2 to include fire-day averages and study averages on the individual 2 s data. We have not included standard deviations of the 2 s data points since this statistic could be improperly interpreted as a measure of uncertainty in the EMR. The study average EFCO value has been revised to be displayed with one decimal number.

R3.23. P72 (Table 3): Why are the average EF values for CO2 and CH4 different to the study average values in Table 2 (EFCO2=1600 g kg-1 in Table 3 but 1596 g kg-1 in Table 2)?

A3.23. The values in Table 3 were a typo that has been corrected in the revised Table 3. The values in the original Table 2 are the correct values.

R3.24. P73 (Table A1): Please add, if possible, information on the fire season and the fuel moisture.

A3.24. We have included the month burn and fuel moisture (when available) to Table A1.

R3.25. P74 (Figure 1): please specify to what date the MODIS Burn Scars and Hotspots refer to.

A3.25. We modified the Fig. 1 caption as "Figure 1. Region of smoke sampling, fire perimeters, and area of active burning for Saddle Complex on August 24, 2011. The MODIS active fire detections and MODIS burn scars are from August 24, 2011."

R3.26. P75 (Figure 2): Helpful would be to see the MCE as additional variable.

A3.36. We have decided not to include MCE. We do not believe that it is particularly helpful.

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/13/C969/2013/acpd-13-C969-2013-supplement.pdf

---

Interactive comment on Atmos. Chem. Phys. Discuss., 13, 33, 2013.