Review of "Daily burned area and carbon emissions from boreal fires in Alaska" by S. Veraverbeke, B. M. Rogers, and J. T. Randerson

Overview

Much research has been carried out over the past two decades to develop and improve approaches to estimate carbon emissions from boreal forest wildland fires, with many studies focused on the Alaskan boreal forest region. An important element of this previous research has been focused on determining the factors that control burning of surface organic layers common to black spruces forests and lowland areas in Alaska, driven by the recognition that the burning of these surface organic layers represent a significant, if not the dominant, source of carbon emissions from fires in this region (see, e.g., French et al. 2005). The manuscript by Veraverbeke et al. represents the second paper by this group in this topic area, and builds to some degree on the previous research carried out on this topic by other researchers.

On the positive side, the study presented in this manuscript will result in a published dataset of carbon emissions for Alaska which may represent an improvement in terms of spatial/temporal resolution from the global fire carbon emissions database (GFED) that has been created by a group that includes an author of this study. In addition, the use of satellite-derived estimates of the density of forest cover to calculate above-ground C emissions represents an advance over methods used in previous studies. Overall, however, I think there are several important issues that need to be addressed before a decision can be made as to whether or not this manuscript merits publication. These issues include: (a) The manuscript fails to provide a framework their approach and results based upon addressing critical uncertainties in previous methods used to estimate C emissions from wildfires in Alaska, in particular, in the introduction, discussion, and conclusions; (b) The performance of the ground-layer C emissions model for black spruce forests is much poorer compared to previous approaches. There are a number of reasons for this, many of which are related to issues with the overall design of the study; and (c) The approach used to estimate uncertainty needs to be clarified and a more thorough discussion of the sources of uncertainty is needed. Details of my concerns in these areas are presented below.

Primary Concerns

a. The context of the study in relation to previous research

Reducing uncertainties in fire C emissions from Alaskan boreal forests

Since the mid-1990s, there have been a number of studies whose objectives were to improve understanding of the role of fire on carbon cycling in the boreal forest region of Alaska, which in turn, has provided the basis for improving models of C cycling, as well as models that estimate direct C emissions from fires. This research has focused on improving pyrogenic C-emissions through use of geospatial datasets including, fire perimeters and remotely-sensed products to determine areas burned during fires and fuel types that are burned during fires. Research has also been carried out on mapping of fire severity using satellite imagery, which as discussed below, has not resulted in reliable approaches. Considerable research has also focused on collecting field data needed to improve understanding of the factors controlling the burning of surface organic layers in black spruce forests, which represent a significant source of emissions during fires in North American boreal forests. Many studies have been carried out in a coordinated fashion that involves a number of researchers (e.g., see numerous publications on fire impacts on boreal forest carbon emission and carbon cycling research carried out by Barrett, French, Genet, Hoy, Kasischke, Li, McGuire, Turetsky, and Yuan). The most comprehensive study based on the research of this group on estimating direct C emissions from boreal forest fires in Alaska is Kasischke and Hoy (2012). In addition, recent efforts have provided newer methods for addressing key uncertainties in estimating C emissions from fire, including modeling of ground-layer consumption in black spruce forests (Barrett et al. 2011; Genet et al. 2013), and accounting for the effects of more frequent reburning of stands (Hoy 2014).

This background is presented to make the point that given the degree of systematic research that has been directed towards improving models on the impacts of fires on the boreal forests in Alaska, it is important that new methods to estimate C emissions from fires should be based on identification of approaches that can be used to address existing uncertainties in the previous approaches. In their introduction, the authors do not a discuss what they feel are the key uncertainties in fire C emission estimation approaches, and do not present a rationale for how their alternate methods will address these key uncertainties. Given the breadth and depth of previous work in this area, this context should be provided.

Relation of the results to previous studies

The authors do not provide a detailed enough discussion of the results from their study to those from previous studies. In particular, there should be a discussion of how the performance of their model of ground-layer carbon consumption varies from other recent efforts, including Barrett et al. (2011) and Genet et al. (2013). In addition, the authors do not compare the results from their approach to those from other recent studies, including Kasischke and Hoy 2012 and Tan et al. 2007), and discuss why the results are different. Factors that could lead to differences that need to be discussed include: (a) variations in estimation of burned area for different years; (b) differences in fuel categories used by the different studies; (c) differences in average fuel consumption for different fuel types (e.g., conifer forests, deciduous forests, shrublands, etc.); and (d) differences for different fuel types (e.g., ground-layer fuel versus aboveground fuel). Such a discussion would help the reader understand why different studies produce different estimates of fuel consumption.

Beginning on 25 of page 604, the authors present a discussion of the relationship of the average ground-layer fuel consumption derived from field studies to those derived from their model, and discuss the need for further measurements of depth of burning based upon the results from their study. This entire passage illustrates a shortcoming of this manuscript in that it fails to correctly relate the research in this paper to research conducted previously. For example, Turetsky et al. (2011) recognized the need to develop a sampling scheme for collection of field data on depth of burning that (a) accounts for factors controlling depth of burning (e.g., topographic position and seasonal timing of fires) and (b) that allowed for scaling of the field results to regional scales through comparison with geospatial information provided by combining information derived from geospatial data. In discussing the design of their study, the authors fail to determine whether or not the dataset they created captures the factors that are known to control depth of burning in black spruce forests

Thus, the observations by the authors that the average model predicted values are different from the field observed averages should not be surprising at all, and is a direct product of the design of the study.

Later on page 607, lines 10-12, the authors state that currently available field data are biased towards high consumption sites further illustrates their lack of understanding of existing data. In particular, the authors only used a fraction of the data from Turetsky et al. (2011), which includes additional data from sites that did not burn under high burning conditions that were not used in this study. A review of the data used by Turetsky et al. (2011) shows that this database on depth of burning in black spruce forests is robust for most of the burn conditions that occur in interior Alaska, except for immature black spruce forests and for sites that burned during late season fires in small fire years.

b. Methods to estimate fuel loads/fuel consumption in Alaskan boreal forests - Suitability of factors used to estimate C emissions from burning of surface organic matter

Previous studies have shown that depth of burning (from which C consumption is estimated) in Alaskan black spruce forests is controlled by a combination of factors that regulated variations in soil moisture, including topographic factors controlling site drainage and seasonal permafrost thawing. While the modeling approach used by the authors (multiplicative, non-linear regression) considered a suite of independent variables that might be related to depth of burning, including (a) slope, (b) aspect, (c) elevation, (d) date of burning, (e) tree cover; and (f) a satellite fire severity index, dNBR, the overall performance of the model does not lead one to believe that it represents an improvement over previous approaches. In particular, the r-squared derived from comparing observed versus predicted values was very low (0.29) (see Figure 3), and the calculated in the equation developed to estimate ground-layer C consumption in black spruce forests (1.99 kg sq m) is 76% of the median ground-layer C consumption produced by the model developed by this study. From Figure 3, there appears to be no relationship between predicted and observed depth of burn for the region where the vast majority of the observations exist (e.g., depth of burn between 10 and 20 cm).

1. I think the authors need to explore other approaches for estimating ground layer consumption that address the shortcomings of their approach. The reason for this recommendation is based on a review of 3 out of the 4 variables selected to model depth of burning/ground C consumption. In section 2.3.3, the authors assert their selection of environmental variables used to estimate fuel consumption was based on an extensive literature review, summarized in Table 1. Ultimately, four of these factors (elevation, pre-fire tree cover, dNBR, and day of year) were included in their model of ground-layer carbon consumption in black spruce forests. I disagree with their assertion that previous studies support selection of 3 out of the 4 selected variables: elevation, pre-fire tree cover, and dNBR.

I used field data from previous studies to evaluate the assertions in this study that depth of burning was controlled by elevation and pre-fire tree cover. I used data from the sites used by by Turetsky et al. (2011), Boby et al. (2010), and Kasischke et al. (2008). These data include pre-fire organic layer thickness, depth of burning, stand basal area for black spruce (which is a measure of pre-fire tree cover), and elevation. I also used depth of burning data and we have collected for additional studies. Using these data, I found that:

(a) Depth of the pre-fire surface organic layers was not correlated to elevation in unburned stands (r-squared = 0.001).
(b) Depth of burning of surface organic layers was not correlated to elevation (r-squared = 0.007).

(c) Depth of burning was not correlated with stand basal area (of overstory black spruce trees) (r-squared = 0.08)

Throughout the introduction, the authors present a narrative to support their use of the dNBR metric to assess variations in fire severity and to estimate fuel consumption in Alaskan boreal forests. The use of dNBR to assess fire severity in the Alaskan boreal forest appears to be supported by a number of peer-reviewed studies where this metric has been used to map fire severity (Duffy et al. 2007; Beck et al. 2011; Jin et al. 2012; Mann et al. 2012). However, I believe from a careful examination of the literature that involves comparing satellite-based indices to surface measures of field data does not support using dNBR as a metric for assessing severity in black spruce forests

While there have been several studies that have shown positive correlations between dNBR and surface measures of severity (Allen and Sorbel 2008/Epting and Verbyla 2005 [both these studies used the same data set], Hall et al. 2008; Rogers et al. 2013) other studies showed no correlation between dNBR and field measures of severity (Hoy et al. 2008; Murphy et al. 2008). The number of sites/plots from where positive correlations between dNBR and suface measures were found (14 fires, 472 plots) were similar in number to those where no correlations were found (8 fires, 374 plots). In addition, French et al. (2008) showed that algorithms based on data collected during the lower-area burned fire years (1999 and 2000 and 2002) by Allen and Sorbel did not predict the field measures of fire severity in the studies of Murphy et al. (2008) and Hoy et al. (2008) using dNBR and field data from the large fire years when on which their studies were based. In addition, in spite of the positive correlations between dNBR and CBI found in the multiple studies cited by the authors from outside of the boreal forest region, Kasischke et al. (2008) showed that the field based Composite Burn Index used to assess burn severity in most studies was not correlated to field measures of specific fire severity characteristics in black spruce forests, including depth of burning of the surface organic layer and measures of canopy burn severity. Importantly, the research by the 7 Alaska researchers summarized by French et al. (2008) also included an assessment of the reasons why the dNBR index does not provide a reliable means for assessing fire severity in Alaskan ecosystems. Verbyla et al. (2008) showed that during the growing season, there is significant variation in the solar zenith angle in Alaska, which results in direct variations in the radiance measured by Landsat in several ways. Verbyla et al. showed there was a 20 to 100% variation in NBR of unburned areas based on variations in solar zenith angles. They also demonstrated that variations in slope and aspect also introduce uncertainties into the NBR metric, so that sites that vary by slope and aspect and have the same fire severity will have different dNBRs. This means that even if positive correlations between dNBR and surface measures of severity exist from specific studies, use of satellite data from throughout the year will introduce errors and uncertainties in satellite-estimates of fire severity. In summary, the detailed research presented by the 7 experts in Alaska present 3 lines of evidence that showed that dNBR index is not suitable for estimating fire severity in the forests of this region. In contrast, the authors of this manuscript argue that dNBR is a suitable index to assess fire severity based on positive correlations between dNBR and CBI found in other regions of the U.S. and by positive correlations found in three separate studies in Alaska. While they use the results from Verbyla and Lord to support their use of dNBR, the field data in this study was collected 23 following the fire event used for this study.

2. Previous studies (Turetsky et al. 2011; Barrett et al. 2011; Genet et al. 2013) have shown that complex topographic variables are more suitable for explaining depth of burning in black spruce forests than use of single topographic measures (such as elevation, slope, aspect). These more complex variables focus on dividing the landscape into discrete landscape units that can be more directly linked to the spatial variations in soil moisture that control depth of burning.

3. I do not believe that using a 500 m DEM provides adequate resolution to map variations in topography that are critical drivers of organic layer thickness and depth of burning in Alaskan black spruce forests. For example, in the collection of our field datasets (e.g., Turetsky et al 2011), we frequently located plots along a transect that crossed the threshold between flat uplands and back slopes or between toe and footslopes (which are poorly drained sites and included in our studies as a lowland) and backslopes. The transitions between flat uplands and backslopes as well as flat lowlands and uplands often occurred over 200 to 300 m. Thus, use of a 500 m DEM is likely to result in the misclassification of the topographic positions in the Turetsky et al. data. Using 60 m DEM data, Kasischke and Hoy (2012) also used a flow accumulation model, which allowed further refinement of identification of poorly drained data, which can be challenging in areas with complex terrains, such as interior Alaska.

4. Other variables have been shown to be important in explaining depth of burning could be considered, including size of the fire year, and size of individual fire events during early season fires (Turetsky et al. 2011).

5. Turetsky et al. (2011) showed that interactions between factors are important in explaining depth of burning in black spruce forests. In particular, variations in depth of burning associated with seasonal thickening of the active layer varied significantly as a function of landscape position. I do not think the modeling approach used by the authors provides for capturing important interactions that control depth of burning.

6. In developing their new approach for estimating depth of burning/ground fuel consumption, the authors do not discuss the suitability of their data set for this purpose. In particular, does the dataset that they developed from their own research and from other studies provide a sampling of the landscape and climatic conditions that are known to control depth of burning in black spruce forests? While one might assume that using the Turetsky et al. (2011) and Boby et al. (2010) (which represents 2/3 of the data used in the study) provides an adequate sample for fire conditions that existed for 2004 (since Turetsky et al. developed a sampling scheme to collect data across different landscape units during early and late season fires), it is very unlikely that the other 40 points used in this study that were collected in fires that burned in other fire years provides enough information to capture the variation in factors controlling depth of burning across topographic positions, variations associated with seasonal thawing of permafrost, and variations in burning associated with different climate conditions. For example,

Turetsky et al. (2011) showed that fire year size was correlated to depth of burn, most likely because fire year size is correlated with the degree of climate-controlled surface drying of organic layers (e.g., dryer conditions that occur during large fire years lead to drier surface organic layers). The 40 points that were from sites sampled in years outside of 2004 provide a very small sample for year with a range of fire sizes (19 points from 2003 – 226,000 ha burned; 17 points from 2010 – 454,000 ha; 2 points from 2002 – 862,000 ha; and 2 points from 2005 – 1,760,000 ha).

c. Uncertainties associated with the C emission estimates

In equation (1) in Section 3.3, the authors present the algorithm used to estimate total uncertainty for their carbon emission estimates and is based on using the above and below ground consumption predictions developed for this study. Based on the RMS uncertainties presented in Figure 3, this equation results in an uncertainty of 2.01 kg C/sq m. However, in the paper, the authors report an uncertainty of only 0.38 kg C/sq m. My question is how did they calculate the uncertainty value presented in the manuscript? The approach they use appears to be based on the standard error for all the output pixels generated by their model, but they do not present a clear explanation of how Figure 9 was created.

In addition, the approach presented in Eq. (1) and in Figure 9 does not account for numerous other sources that will contribute uncertainties to the carbon consumption values associated with their overall methodology, including: (a) uncertainties associated with the calculations of carbon consumption by the Consume model that were used for other vegetation types; (b) uncertainties associated with the scaling the Consume calculations of carbon consumption based on using estimates from their model for black spruce vegetation; (c) the uncertainties in the baseline vegetation cover map (which are discussed but not quantified); (c) uncertainties associated with using 500 m products, especially in topographic information; (d) the uncertainties introduced by using 500 m resolution products for estimation of carbon consumption, where the algorithm themselves are based on using 30 m resolution products; (e) not including dead wood debris in their estimates of total carbon emissions, which Kasischke and Hoy (2012) show represent 5 to 7% of all emissions; and (d) uncertainties associated with the representativeness of the database used to develop the C consumption algorithms.

At the very least, the authors need to provide a discussion on the various sources of uncertainties that are present in their estimates of carbon consumption.

d. Other issues

Clarification of methods

1. Why was it necessary to generate a 30 m DEM for this study, when existing DEM data already exist at 60 m resolution? I would understand creating a 30 m DEM if the authors conducted their analyses at this resolution. But in this study, the authors degraded the 30 m DEM product they developed to 500 m.

2. In section 3.3, more detail is needed on how biomass consumption for other fuel types was estimated, in particular, how they scaled the belowground measurements. First, the actual data used for Consume was based on collection during burning conditions that existed in smaller fire years or during early season fires in a large fire year (see, e.g., http://depts.washington.edu/nwfire/dps/). As such, the conditions used to develop the Consume model for Alaska do not match the range of conditions that existed for many of the fires that occurred during the 2000s, in particular, late season fires during large fire years. Second, scaling fuel consumption in deciduous and white spruce forests forest floors based on deep burning in late season fires does not make sense for these forest types, which do not contain permafrost. In addition, the information presented in Supplementary Fig. 6, ground fuel consumption in white spruce forests is about 2/3 of ground fuel consumption in black spruce forests, while ground fuel consumption in deciduous forests is about 1/3 of that in black spruce forests. Based on data present in the USFS fuel layers for Alaska (http://depts.washington.edu/nwfire/dps/), the max fuel levels for deciduous forests is on the order of 1.2 to 1.5 kg/sq m, while the fuel levels for white spruce forests has a maximum level between 2.2 to 2.5 kg/sq m. According to the approach described by the authors, the max fuel consumption for black spruce ground layer is 8 kg/sq m, which results in a max for deciduous of 2.4 kg / sq m and 5.3 kg / sq m for white spruce, both of which are substantially higher than fuels available for burning in these forest types. Finally, in shrub and grass vegetation types, the foliage and small branches are much less flammable than the foliage in black spruce, and there is likely a much lower level of aboveground fuels in these fuel types than in black spruce forests; thus, using the fuel consumption values for above ground black spruce does not make sense. There is no evidence presented that all shrub and grass lands occur on sites with permafrost. In many instances, these vegetation types are likely the result of regrowing forests following fires. Thus, assuming that the ground-layer fuel consumption in this forest types is the same as in black spruce forests is not justified.

3. Section 2.3.4 – Why use LANDFIRE land cover rather than NLCD. In terms of mapping mature black spruce, the Landfire data set has a much lower accuracy than the North American Land Cover dataset, whose accuracy has been assessed for Alaska (Selkowitz DJ, Stehman SV (2010) A spatially stratified, multi-stage cluster sampling design for assessing accuracy of the Alaska

(USA) National Land Cover Database (NLCD). International Journal of Remote Sensing, 31, 1877–1896). We determined this by using field plots where we collected depth of burning in black spruce forests during the 2003-2005 wildfires in Alaska. The authors should check this. Thus, another source of uncertainty in their study

Other Comments

Page 581 – line 10. The references are incomplete, as they only cite papers that are based on models that use climate as the driver of changes to fire regimes. They should also cite research that shows changes in vegetation cover associated with changes to climate and the fire regime will have negative feedbacks to future burned area (Mann et al. 2012; Kelly et al. 2013)

Page 581 – line 21: Jin et al. and Beck et al. are two examples of studies that use dNBR for assessing fire severity, when in fact, there is no strong evidence that dNBR is a viable metric for doing so. In addition, Beck et al.'s method for identifying late season fires that result in deep burning, severe was flawed, in that the cut-off date for separating early vs. late season fires was early June.

Page 582 – line 3 – Rather than citing their own research, the authors should the research where this approach was first used – Michalek et al. 2000

Page 582, line 27: I would not use modeling studies to support the observation made in this sentence, but rather field-based studies such as Johnstone and Kasischke 2005 and Turetsky et al.

Page 584, line 13: Rather than referring to the most recent papers that support observations made in this sentence, the authors should preferably include the papers where the technique was first introduced, in this case Kasischke and Hoy 2012

Page 582, line 20 – You need to be more specific here – the observations of de Groot et al. (2009) referred only to consumption of ground layer biomass in black spruce forests, and these observations in this paper are not in reference to other fuel types and categories. Except for ecosystems with deep organic layers, the models developed by researchers at the Canadian Forest Service perform quite well for forested area.

Page 582, lines 25-30. I would stick to papers where direct observations of the effects of late season burning have been made, such as Turetsky et al. and Kasischke and Johnstone 2005. The other papers cited here deal with estimating the impacts of late season burning on emissions.

Page 583, lines 1 to 5. The references are not appropriate. Kajii et al. actually show a decrease in total biomass consumption between Aug and Sep, and thus do not support the point of this sentence. Soja et al. provide a range of depth of burning for different ecosystems, but do not specifically cite late season deepening of the active layer as being the driver of deeper burning fires.

Page 583, line 28-30: While these studies showed correlations between NBR and depth consumption, these studies were all conducted in sites where deep burning of the surface organic layer did not occur. This should be noted.

Page 584, line 15: Note that Kasischke and Hoy used MODIS Hotspot data to develop daily fire progression maps, which were combined with burned area maps derived from Landsat dNBR products to create daily burned area products. This is a fundamentally different approach than used in this study, and provides much finer spatial information (by an order of magnitude) on patterns of burning than can be derived from using 500 m MODIS burned area maps, the approach used in this study.

Page 585, lines 19-23: This sentence presents an overly simplistic model of the distribution of black spruce in Alaska. Recent studies have shown that black spruce is widely-distributed than just on north aspect slopes and in lowlands. The data from Turetsky et al. provide evidence that mature black spruce is distributed across all aspects on backslopes.

Page 589, line 21-22: This statement is not true. AKFED does not estimate soil moisture from elevation and time of burning, but correlates burn depth and carbon consumption to these variables.

Page 599, line 5: Also, Kasischke and Hoy reported that 20% of the areas within the perimeters of the fires they studied.

Page 599, line 15-20: This may not be true based on Jones et al. (2013) who identified several large tundra fires that had previously occurred on the North Slope (JOURNAL OF GEOPHYSICAL RESEARCH: BIOGEOSCIENCES, VOL. 118, 1–11, doi:10.1002/jgrg.20113, 2013)

Page 601, line 9 to 25: This material should go into the methods and be reported in the results section

Page 605, line 8-9. Since neither Duffy et al. nor Beck et al. actually used field data to quantify fire severity, this sentence does not make sense.

References Cited in this Review

Allen JL, SorbelB(2008)Assessing the differenced Normalized Burn Ratio's ability to map burn severity in the boreal forest and tundra ecosystems of Alaska's national parks. International Journal of Wildland Fire 17,463–475.

Barrett, K., A. D. McGuire, E. E. Hoy, and E. S. Kasischke. 2011. Potential shifts in dominant forest cover in interior Alaska driven by variations in fire severity. Ecol. App. 21:2380-2396.

Beck, P. S. A., Goetz, S. J., Mack, M. C., Alexander, H. D., Jin, Y., Randerson, J. T., and Loranty, M. M. 2011. The impacts and implications of an intensifying fire regime on Alaskan boreal 15 forest composition and albedo, Glob. Change Biol., 17, 2853–2866.

Boby, L. A., E. A. G. Schuur, M. C. Mack, D. L. Verbyla, and J. F. Johnstone. 2010. Quantifying fire severity, carbon, and nitrogen emissions in Alaska's boreal forest Ecological Applications 20:1633-1647.

Duffy PA, Epting J, Graham JM, Rupp TS, McGuireAD (2007) Analysis of Alaskan burn severity patterns using remotely sensed data. International Journal ofWildland Fire 16, 277–284.

Epting J, Verbyla D, Sorbel B (2005) Evaluation of remotely sensed indices for assessing burn severity in interior Alaska using Landsat TM and ETM+. Remote Sensing of Environment 96, 328–339.

French, N.H.F., P. Goovaerts, and E.S. Kasischke. 2004. Uncertainty in Estimating Carbon Emissions from Boreal Forest Fires, Journal of Geophysical Research,109, D14S08, doi:10.1029/2003JD003635.

French, N.H.F., J.L. Allen, R.J. Hall, E.E. Hoy, E.S. Kasischke, K.A. Murphy, and D.L. Verbyla. 2008. Using Landsat Data to assess fire and burn severity in the North American boreal forest region: an overview, International Journal of Wildland Fire, 17, 443-462.

Genet, H., A. D. McGuire, K. Barrett, A. Breen, E. S. Euskirchen, J. F. Johnstone, E. S. Kasischke, A. M. Melvin, A. Bennett, M. C. Mack, T. S. Rupp, A. E. G. Schuur, M. R. Turetsky, and F. Yuan. 2013. Modeling the effects of fire severity and climate warming on active layer and soil carbon dynamics of black spruce forests across the landscape in interior Alaska. Environ. Res. Lttrs. 8.

Hall RJ, Freeburn JT, de Groot WJ, Pritchard JM, Lynham TJ, Landry R (2008) Remote sensing of burn severity: experience from western Canada boreal fires. International Journal ofWildland Fire 17, 476–489.

Hoy, E. E. 2014. Impacts of a changing fire frequency on soil carbon stocks in interior Alaskan boreal forests. University of Maryland PhD Dissertation, 95 pp.

Hoy, E. E., N. H. F. French, M. R. Turetsky, S. N. Trigg, and E. S. Kasischke. 2008. Evaluating the potential of the normalized burn ratio and other spectral indices for assessment of fire severity in Alaskan black spruce forests. Int. J. Wildland Fire 17:500-514.

Jin, Y., Randerson, J. T., Goetz, S. J., Beck, P. S. A., Loranty, M. M., and Goulden, M. L. 2002. The influence of burn severity on postfire vegetation recovery and albedo change during early succession in North American boreal forests, J. Geophys. Res., 117, G01036, doi:10.1029/2011JG001886.

Kasischke, E. S., and E. E. Hoy. 2012. Controls on carbon consumption during Alaskan wildland fires. Global Change Biology 18:685-699.

Kasischke, E.S., M.R. Turetsky, R.D. Ottmar, N.H.F. French, G. Shetler, E.E. Hoy, and E.S. Kane. 2008. Evaluation of the composite burn index for assessing fire severity in Alaskan black spruce forests, Int. International Journal of Wildland Fire, 17, 515-526.

Mann, D., T. Rupp, M. Olson and P. Duffy. 2012. Is Alaska's Boreal Forest Now Crossing a Major Ecological Threshold? Arctic, Antarctic, and Alpine Research, 44(3):319-331. 2012.

Murphy KA, Reynolds JH, Koltun JM (2008) Evaluating the ability of the differenced Normalized Burn Ratio (dNBR) to predict ecologically significant burn severity in Alaskan boreal forests. International Journal of Wildland Fire 17, 490–499.

Rogers, B. M., Veraverbeke, S., Azzari, G., Czimczik, C. I., Holden, S. R., Mouteva, G. O., Sedano, F., Treseder, K. K., and Randerson, J. T. 2014. Quantifying fire-wide carbon emissions in interior Alaska using field measurements and Landsat imagery, J. Geophys. Res., 119, 1608–1629, 2014.

Selkowitz DJ, Stehman SV (2010) A spatially stratified, multi-stage cluster sampling design for assessing accuracy of the Alaska (USA) National Land Cover Database (NLCD). International Journal of Remote Sensing, 31, 1877–1896.

Tan, Z., Tieszen, L. T., Zhu, Z., Liu, S., and Howard, S. M.: An estimate of carbon emissions from 2004 wildfires across Alaskan Yukon River Basin, Carbon Balance and Management,25 2, 1–8, 2007.

Turetsky, M. R., E. S. Kane, J. W. Harden, R. O. Ottmar, K. L. Manies, E. Hoy, and E. S. Kasischke. 2011. Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. Nature Geoscience 4:27-31.

Verbyla, D., E.S. Kasischke, and E.E. Hoy. 2008. Seasonal and topographic effects on estimating fire severity from remote sensing data, International Journal of Wildland Fire, 17, 527-534.