

**Great Rivers CESU
SOW**

Between

NATIONAL PARK SERVICE

And

**UNIVERSITY OF ILLINOIS at URBANA-CHAMPAIGN
(CESU Host, the University of Missouri – CA No. H60000 80300)
Task Agreement Number: P11AC60520**

Project Title: The role of tundra burning in carbon cycling: Radiocarbon analysis of recent burns in the Noatak National Preserve, Alaska

**Date: May 5, 2014
Final Report Prepared By:**

**Principal Investigator:
(Cooperator)** Dr. Feng Sheng Hu, Professor and Head
Department of Plant Biology
University of Illinois at Urbana-Champaign

Park Representative: Jennifer L. Barnes, Regional Fire Ecologist
Alaska Regional Office NPS

Research Assistant: Dr. Carolyn Dash, Postdoctoral Associate
Department of Plant Biology
University of Illinois at Urbana-Champaign

Abstract

Increased burning of tundra ecosystems as a result of anthropogenic climate warming may cause sudden releases of the enormous amount of soil carbon that has accumulated during the late Quaternary. The primary goal of this project was to assess the age of carbon consumed in the record-setting tundra fires of summer 2010 in the Noatak National Preserve in northwestern Alaska. To achieve this goal, we collected soil monoliths from burned and unburned areas in four areas for ^{14}C analysis. These ^{14}C data were also used to estimate carbon accumulation rates and discuss the biogeochemical implications of arctic tundra fires. Charcoal flakes from the burns of summer 2010 yielded ^{14}C ages of AD 1952-2006, with an average of AD 1981. These data indicate that the carbon consumed in the 2010 fires will recover through vegetation succession, assuming that the fire-return interval will remain >60 years. However, at 25 cm below surface, the mean soil ages differ significantly among different burn-severity classes: (1) unburned ($n=8$; mean age = 50 years old), (2) low-to-moderate severity ($n=10$; mean age = 200 years old), and (3) moderate-to-high severity or twice burned ($n=6$; mean age = 850 years old). This pattern suggests that the soil carbon pool is vulnerable to future fires in areas that have burned repeated over the past few decades. The mean carbon accumulation rate is $85.97 \text{ gC}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ across all of our sites, with the monolith means ranging from 8.12 to $214.31 \text{ gC}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$. Comparisons of these estimates of carbon accumulate rates with eddy-covariance measurements of net ecosystem exchange suggest that ecosystem modeling of carbon dynamics could be improved by incorporating the dramatic variability of carbon turnover rates in different soil horizons. Overall our results provide information needed for land and fire managers to make sound decisions about fire management activities and future repercussions.

Background and Purpose

Evidence suggests that tundra burning is increasing in the Arctic, likely in response to climatic warming and associated changes in fuel characteristics. For instance, in 2010 the Noatak National Preserve had 37 fires that burned more than 106,696 acres – a record-setting number of fires on an annual basis for this area. Increased tundra burning has far-reaching ecological and socio-economic implications. Tundra burning may fundamentally alter the soil carbon budget (Racine, Dennis & Patterson 1985; Racine, Johnson & Viereck 1987; Wookey *et al.* 2009; Mack *et al.* 2011). In particular, approximately one third of the soil carbon in global terrestrial ecosystems is stored in Arctic and subarctic regions (McGuire *et al.* 2009). A major concern is that increased tundra burning may cause rapid releases of this carbon into the atmosphere, thereby serving as a positive feedback to climatic warming. Alternatively, tundra burning may primarily consume biomass that has accumulated over the past several years to decades, with minimal effects on the long-term carbon storage. To address these alternative hypotheses, we collected charcoal samples from the 2010 burns in the Noatak National Preserve (NOAT) in northwestern Alaska for ^{14}C analysis. Here we report these ^{14}C data to answer the question: What is the age of organic matter (OM) consumed during a tundra fire? We also measured fire severity at our study sites, and interpreted our ^{14}C results in the context of fire severity. Furthermore, we

estimated carbon accumulation rates to shed light on the biogeochemical implications of arctic tundra fires.

Study Area

We collected organic soil monoliths and recorded burn severity from four large 2010 wildfires in NOAT (Fig. 1). The average maximum January and July temperatures of the region are -15.66°C (SD = 4.65) and 15.12°C (SD = 1.74), respectively; mean annual precipitation is 251 mm (SD = 66), with 52% falling between July and September (Western Regional Climate Center, 1950-2012 observations for

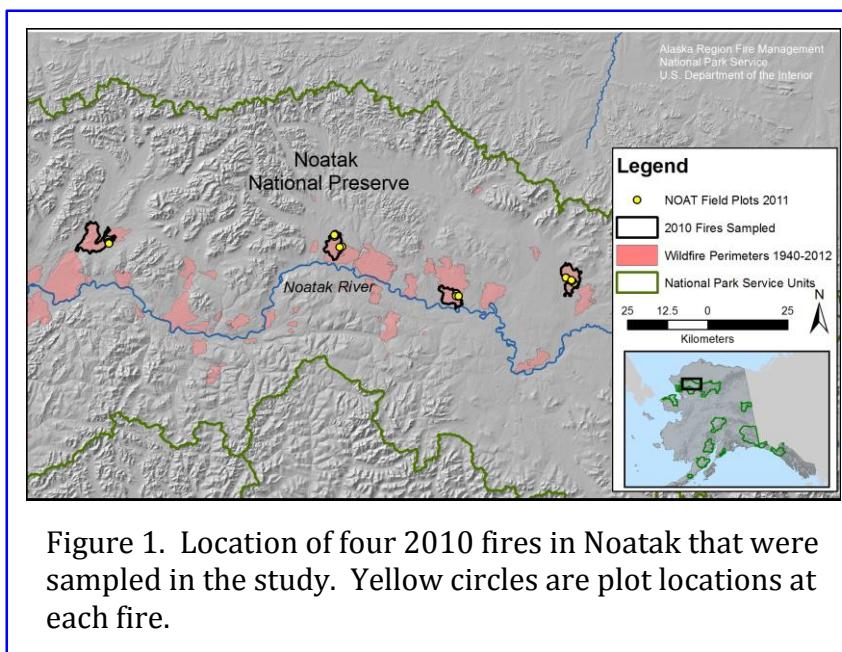


Figure 1. Location of four 2010 fires in Noatak that were sampled in the study. Yellow circles are plot locations at each fire.

Kotzebue, accessed March 2013; *available online*).¹ Over the past 60 years the Noatak Valley has experienced periodic large fires and frequent small lightning-caused fires from late May through early August (DOI Wildland Fire Management Information – WFMI database). The median fire return interval is estimated to be 150 to 220 years over the past 2000 years (Higuera *et al.* 2011). Vegetation is dominated by tussock-shrub tundra (including *Eriophorum*, *Carex*, *Ericaceae*, *Betula*, *Salix*), birch-ericaceous shrub tundra, and willow (*Salix*) or alder (*Alnus*) shrub communities, with white spruce (*Picea glauca*) reaching its up-valley limit along the Noatak River and adjacent drainages.

Materials and Methods

The research was conducted at four of the 2010 fires in NOAT (Table 1). The fires sampled were selected to ensure spatial representation of the fires in Noatak valley, yet logistically feasible in a very remote area. One fire that was selected burned through portions of a 2002 fire. Plot locations were selected based on a randomized stratified selection of burn severity classes based on satellite derived burn severity maps for each fire. Sites were limited to lower terrain tussock-shrub tundra or ericaceous shrub tundra as these were the dominant vegetation types and to maximize organic soil depths. At each fire six plots were located, stratified by the following fire severity classes: 2 within unburned areas, 2 within low to moderate severity sites, and 2 within high severity sites.

¹ <http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ak5076>

Burn severity GIS data layers were developed for the four fires by applying the Normalized Burn Ratio (NBR) to pre- and post-fire Landsat imagery based on the Landscape Assessment methods developed by Key and Benson (2006). All image processing for the 4 fires was conducted by the USGS EROS Data Center as part of the Monitoring Trends and Burn Severity Mapping Project. The actual severities of the sites and organic monolith samples varied slightly from the proposed sampling scheme.

Twenty-meter-diameter circular plots were utilized to record the following information: dominant vegetation classification, ocular estimates of plant, non-vascular and ground cover, and burn severity scores based on the Composite Burn Index methods (Key and Benson 2006). At each plot one 20 cm x 20 cm organic soil monolith (OM) was cut to mineral soil or point of restriction by permafrost or seasonal frost. The organic soil horizon thicknesses were measured, dominant bryophyte types were identified if feasible, microsite burn severity was recorded and photos were taken of each OM sample. Samples were wrapped in plastic wrap/aluminum foil and stored in coolers until shipped to the University of Illinois, where they were stored in a -4°C cold room.

Table 1. Four 2010 fires (from East to West) sampled in this study. The Lake Tutusirok fire burned into the 2002 Cottonwood Bar fire.

Fire Name	Fire Code	Latitude Fire Origin	Longitude Fire Origin	Fire Size (Acres)
Navashak Lake East	FJB3	68.13639	-157.959716	9,890
Nanielik Creek	FJ1V	68.087219	-158.884719	6,538
Lake Tutusirok	FH8Z	68.17530	-159.69560	7,387
Rok North	FH6Y	68.143608	-161.526774	13,106

To determine the age of the carbon released during tundra fires, we selected plant macrofossils (e.g., charcoal flakes, seeds) from the soil monoliths for radiocarbon dating. Each sample was treated with sodium metaphosphate and sieved through 180 µm mesh to concentrate plant macrofossils. Four samples were selected from the top of each of the monoliths from the burned sites, including three charcoal pieces and one non-charred macrofossil, and one macrofossil was selected from each of the middle and bottom samples. For the 8 monoliths from unburned sites, only the bottom of each monolith was sampled because the tops of these monoliths are representative of the present day. Non-charcoal macrofossils primarily consisted of leaves, moss, decomposed wood, and/or sedges; roots were specifically avoided because roots of live plants can penetrate into lower soil horizons. In a few cases, we also sampled the centimeter immediately below the top sample to help constrain the ages from the top of the monoliths. Samples were prepared for radiocarbon dating with an acid-base-acid procedure (Oswald *et al.* 2005) and submitted to the Lawrence Livermore National Laboratory (LLNL) for accelerator-mass-spectrometry ¹⁴C analysis. The ¹⁴C dates were converted to calendar years with Calib 6.1.1 using the IntCal09 dataset (Reimer *et al.* 2009) and with CALIBomb (Levin *et al.* 2008).

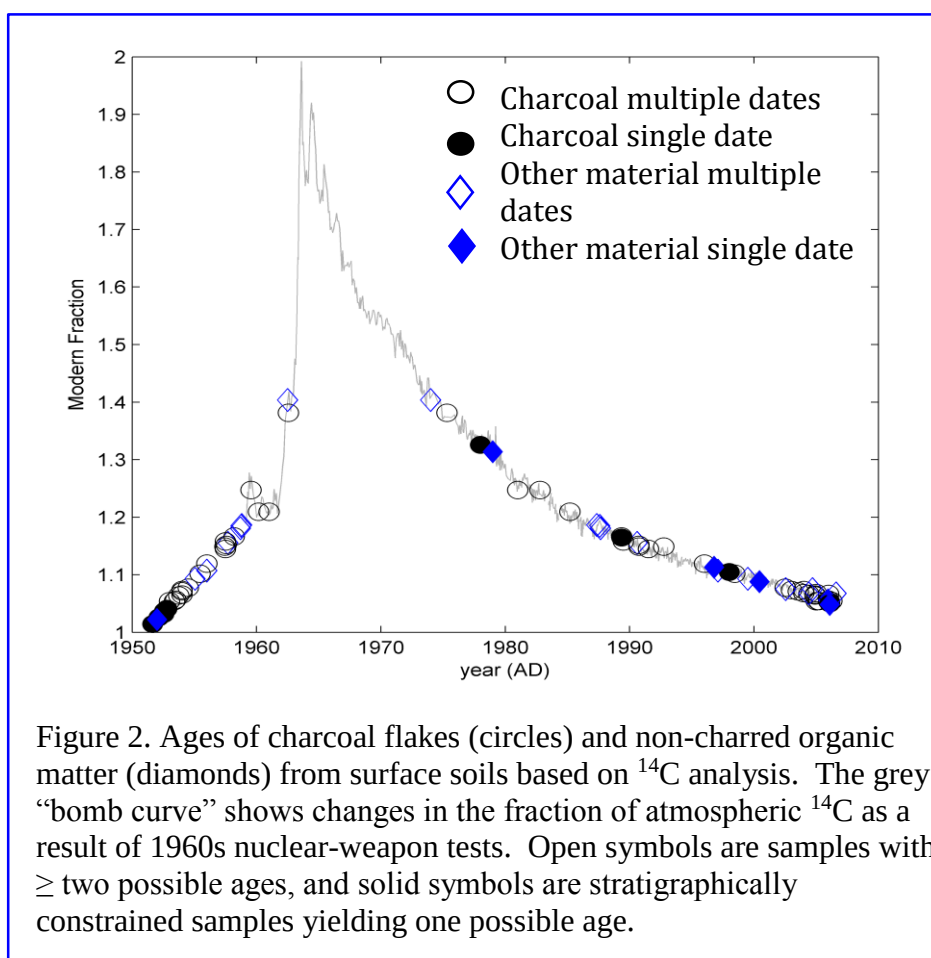
We also analyzed carbon content at contiguous 1-cm intervals in each monolith. This is not a component of our proposed work, but we took advantage of the availability of the soil samples and ¹⁴C ages to estimate carbon accumulation rates in the tundra

ecosystems of NOAT at no additional cost to the project. A rectangular prism of each monolith (from top to bottom) was removed, sliced at 1-cm intervals, and the bulk density of each sample was calculated. A CHN analyzer at the Institute for Genomic Biology at the University of Illinois was used to measure the carbon and nitrogen percentages of the tundra samples. The C percentages were converted to accumulation rates ($\text{gC}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) by multiplying $\text{gC}\cdot\text{m}^{-3}$ with m/year , the latter of which was estimated from the ^{14}C ages of the soil profiles.

Results and Discussion

We obtained a total of 91 radiocarbon dates, with 51, 16, and 24 from the top, middle, and bottom of the soil monoliths, respectively. Charcoal flakes from the surface soils, which most likely came from the burns of summer 2010, yielded ^{14}C ages of AD 1952-2006, with an

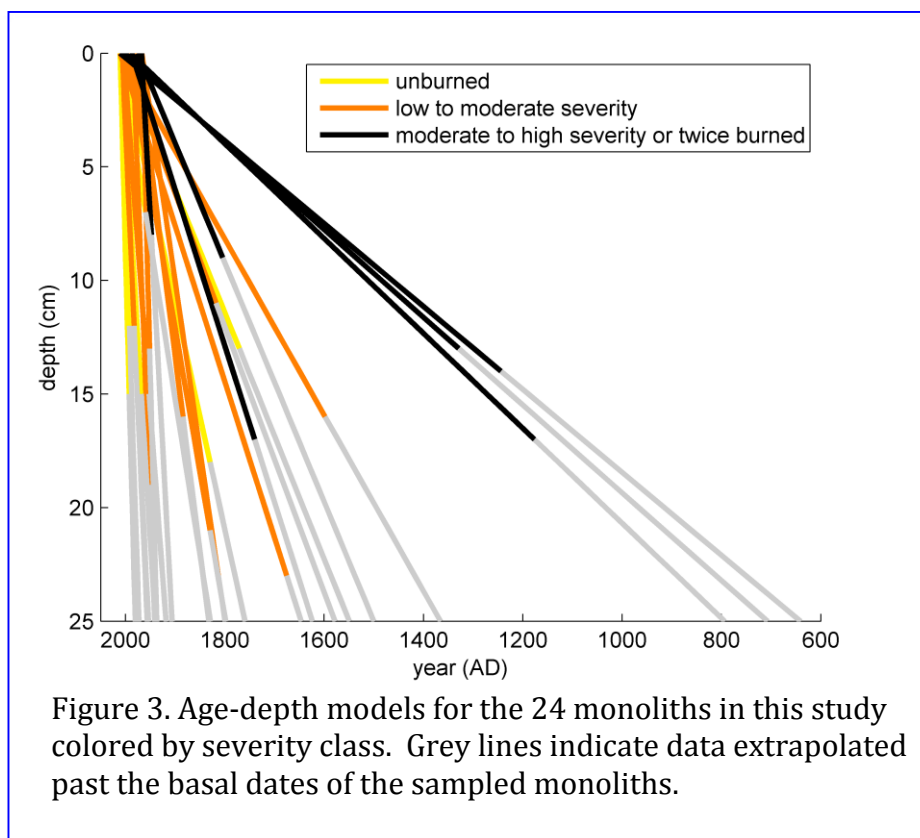
average of AD 1981 (Figure 2). These ages provide unambiguous evidence that the summer 2010 burns consumed biomass that is <60 years old. The non-charcoal samples from surface soils were dated to AD 1952-2007, with a mean of AD 1983. There is no statistical difference in the age distributions between charcoal and non-charcoal samples (t -test, $t = -0.41$, $p = 0.68$). Furthermore, no clear relationship exists between surface-charcoal ages and fire-severity classes.



The basal ^{14}C ages of the soil monoliths provide information on the vulnerability of older C to tundra burning. These ages range from AD 1991 (NAN-F01A, 12.5 cm) to AD 917 (Tut-D-02A, 17.5 cm) at our sites. Direct comparisons of these basal ages among sites are not meaningful because the bottom depths differ among the monoliths. If we extrapolate the depth-age models to the same depth at 25 cm below surface, the soil samples range from ~ 30 to ~ 1400 years old (Figure 3). No clear relationship exists between soil ages at

25 cm and burn severity, probably reflecting spatial variability in the rates of carbon accumulation through the history and/or carbon combustion in fires at individual sites. However, at 25 cm below surface, the mean soil ages differ significantly if we group the soil monoliths into three groups based on burn-severity classes: (1) unburned ($n=8$; mean age = 50 years old), (2) low-moderate severity ($n=10$; mean age = 200 years old), and (3) moderate-high severity or twice burned ($n=6$; mean age = 850 years old) ($F=9.46$, $p=0.0012$; Fig. 3). This pattern is consistent with the fact that fire-severity classification was based on our field assessment of the amount of organic matter consumed in the fires. It suggests that the soil carbon that has accumulated over the late Quaternary is more vulnerable to future fires in areas of repeated burns over the past few decades. However, this pattern is based on only two sites with repeated burns, and thus verification at other sites of repeated burns is needed.

A recent fire-history reconstruction on the basis of charcoal analysis of lake sediments indicates that the mean fire return intervals ranged from 135 to 300 years over the past 2000 years in NOAT (Higuera *et al.* 2011). Chronosequence analysis of tundra fires of the past decades in the Alaskan Arctic also reveals that surface properties, including vegetation greenness as inferred from a MODIS enhanced vegetation index, appear to have recovered rapidly (within 40 years) (Rocha *et al.* 2012). Given the average age of AD 1981



from the surface-soil charcoal samples at our study sites, the carbon released from the tundra ecosystems by the 2010 fires in NOAT will recover through vegetation succession. Thus these tundra fires may not have long-term consequences on the carbon storage of the tundra ecosystems if the fire return intervals remain the same as in the past. However, this does not imply that fires do not affect other important aspects of tundra ecosystems. For example, fires alter the composition of tundra plant communities, and the recovery of lichens and bryophytes is slow. In addition, there is evidence that tundra fire frequency has increased in the Alaskan Arctic over the past two decades (Rocha *et al.* 2012), and this trend will likely continue in the coming decades as a result of anthropogenic climate

change. Increased fire frequency and repeated burns in the same areas may lead to combustion of much older carbon than that consumed in the 2010 fires.

The soil monoliths have a mean %C range of 23.0-46.7 and a mean %N range of 0.6-1.6 (dry weight). The mean C:N ratio is 38.2 (SE $\pm$ 2.8), but it varies with burning. Unburned monoliths have a mean C:N ratio of 46.6 (SE $\pm$ 1.5), whereas burned monoliths have a mean C:N ratio of 33.7 (SE $\pm$ 0.62, Figure 3). The higher mean of C:N ratios for the unburned sites than for the burned sites likely reflects that labile organic matter in the C pool of rapid turnover has been consumed in fires at the burned sites. The mean C pool in the top 5 cm, 1312.6 gC•m⁻² (SE $\pm$ 162 gC•m⁻², n=23), is similar to a previously published estimate from the Alaskan tundra (1538 gC•m⁻²; SE $\pm$ 109 gC•m⁻², n=20, Mack *et al.* 2011).

The mean C accumulation rate is 85.97 gC•m⁻²•yr⁻¹ across all of our sites, with the monolith means ranging from 8.12 (TutD04A) to 214.31 (NANF01A) gC•m⁻²•yr⁻¹. In general, C accumulation rates are higher at unburned sites or low-severity burns than at moderate/high-severity burns. However, there are outstanding exceptions. For example, the mean accumulation rate is 210.05 gC•m⁻²•yr⁻¹ at NAVH03A, a moderate/high burn, and 20.99 gC•m⁻²•yr⁻¹ at NANF07A, an unburned site. Net ecosystem exchange (NEE) based on eddy covariance measurements provides information on ecosystem C balance and can be compared with C accumulation rates from soils. In the area of Anaktuvuk River Fire near Toolik Lake, Rocha and Shaver (2011) reported a carbon sink of 44.63 gC•m⁻² for the period of May 1 through August 28 for unburned tundra. Taking into consideration autotrophic and heterotrophic respiration in the non-growing season, C accumulation in the modern tundra may be $\sim$ 20 gC•m⁻²•yr⁻¹. This estimate is substantially lower than the mean of 85.97 gC•m⁻²•yr⁻¹ across our sites, and an order of magnitude smaller than the highest end (NAVH03A) of the range of C accumulation rate at our sites. A plausible explanation is that NEE is a measure of C balance for the entire ecosystem without considering the dramatic spatial heterogeneity of C cycling. The high numbers from our study reflect that our soil monoliths include organic matter of the uppermost soil horizon, which is relatively labile with rapid turnover rates. Thus the actual long-term accumulation rates of C are likely much lower. This argument is supported by our estimates of C accumulation at the burned sites where the uppermost organic matter has been consumed in recent fires. For example, the mean C accumulation rate is 8.84 gC•m⁻²•yr⁻¹ at TutD02A and 8.12 gC•m⁻²•yr⁻¹ at TutD04A, the two sites that have experienced moderate/high-severity burns twice over the past 60 years. These estimates underscore the vulnerability of tundra C stocks to repeated fires. For example, a removal of 15-cm soil in a fire would result in the loss of C that has accumulated over a much longer period at a 2X burned site than at an unburned site. These data also imply that ecosystem modeling of future C dynamics could be made more realistic by incorporating the dramatic variability of C turnover rates in different soil horizons.

Management Implications

Wildfire has been recognized as a natural part of the tundra ecosystem in northwestern Alaska, particularly within the Noatak drainage (Racine, Dennis & Patterson 1985; Higuera *et al.* 2011), while other tundra regions appear to have less frequent fires (Hu *et al.* 2010; Rocha *et al.* 2012). Prior to 1980 the policy for fire in Alaska required the

immediate suppression of all wildfires. In the early 1980s it was recognized by the land and fire protection agencies within Alaska that an improved system was needed for establishing fire response priorities, in order to accomplish land-use objectives in the most cost-effective manner. Statewide fire management plans were developed; these plans recognized the benefits of fire and were not solely focused on fire suppression (Todd & Jewkes 2006). The bases of these plans have provided direction for fire management activity within Alaska over the past 30 years. Under the Alaska Interagency Wildland Fire Management Plan, land management agencies determine the desired fire protection option for their lands and resources: Critical, Full, Modified, or Limited. The protection categories establish priorities for allocating fire-fighting resources with the Critical category being the highest priority and Limited the lowest. These categories are based on values to be protected, as well as the managing agency's resource management objectives, policies and mandates.

The mission of the National Park Service (NPS) is to preserve and protect the natural, cultural, and historic resources within park units for future generations; which can include preserving natural processes and the ecological diversity of the landscapes. The primary objective for managing wildfires in Noatak National Preserve has been to maintain the natural processes and to allow fire to fulfill its natural role (including the naturally occurring spectrum of wildfire intensities and effects) while also ensuring the safety of life, property, and sensitive resources (Western Arctic National Parklands, Fire Management Plan for Western Arctic Parklands, National Park Service, 2012). Approximately 90% of NPS lands in Alaska are managed under "Limited Protection" fire management option; within this fire management option most natural ignitions are managed for resource purposes, while protecting identified sites from fire if needed. Under future climate scenarios, managing landscape level fires may become increasingly complex for wildland fire management programs. New strategies to manage for biodiversity, carbon and other important natural resource values may need to be considered.

Climate change is likely to impact the occurrence, extent, and severity of fires in these arctic and subarctic regions of Alaska and may have cascading effects on other ecosystem processes. Based on recent burn severity mapping work (Allen & Sorbel 2008; unpublished Barnes) a majority of the areas burned in the tundra regions of Noatak are low to moderate severity; however this may change. This study indicates that if tundra fires continue under the current fire regime, with fires re-occurring every 150-220 years (Higuera *et al.* 2011), the natural growth and re-vegetation will likely replenish the carbon that was released during the previous fire. However, if fires begin to burn more frequently (repeat fires) and/or burn deeper into the organic soils, older carbon will likely be released. In addition this study provides data for understanding carbon dynamics in tundra ecosystems and highlights the large variability of carbon turnover rates in different soil horizons. This information is important for spatially explicit ecosystem models (e.g., DOS-TEM; Yi *et al.* 2010) that are used to project carbon dynamics in relation to future fire-regime scenarios.

The decision to manage fires differently based on carbon emissions or other factors (e.g. wildlife habitat) will be reliant upon the land managers to weigh the effects on global carbon emissions, ecosystem management, and the impacts of fire suppression on the landscape. The costs of fire suppression in remote areas will need to be weighed against the risk of fires in more populated areas. Research such as this study, provides information

that is needed for land and fire managers to make sound decisions about fire management activities and future repercussions.

Future Work Needed

This study is among the first to offer information on the age of carbon consumed in tundra fires and on soil carbon accumulation rates in relation to tundra fires. As such, our results cannot be evaluated with data from elsewhere, other than the limited comparisons with those from the 2007 Anaktuvuk River Fire cited in the above text. To our knowledge, nowhere else on Earth can we find tundra ecosystems that have burned nearly as frequently as those of NOAT and the Seward over the historic period, with rich background information collected by NPS fire scientists and managers. Thus the historic fires of these regions offer a unique outstanding opportunity to evaluate how the projected increase in tundra burning in the 21st century will affect the structure and function of tundra ecosystems in the context of anthropogenic climate change. Our preliminary results from the four 2010 fires in NOAT should be evaluated with data from similar studies of other fires in these regions. In particular, our data suggest that the soil carbon that has accumulated over the late Quaternary is more vulnerable to future fires in areas of repeated burns over the past few decades. However, this pattern is based on only two sites with repeated burns, and thus verification at other sites of repeated burns is needed. Furthermore, our fieldwork was conducted in early summer when the permafrost table was too shallow for us to collect samples in deeper soil horizons. Fieldwork in future studies should be done in August to ensure collection of deeper/older soils in order to improve our understanding soil carbon dynamics in tundra ecosystems. Finally, developing scenarios of future tundra-fire regimes to guide management and projecting the biogeochemical consequences of future tundra burning will require that we incorporate our field data into ecosystem models designed to study tundra ecosystems. This will require collaboration with ecosystem modelers working in Arctic regions.

Deliverables and Outreach

The following research briefs, outreach products and presentations have been completed as a result of this study:

Barnes, J.L. 2013. Does burn severity effect the age of soil carbon released during a tundra fire? A case study from Noatak National Preserve. RxEffects, NPS Fire Ecology Program. Vol 1, Issue 12, pg. 8. <http://www.nps.gov/fire/wildland-fire/resources/documents/rx-effects-summer-2013.pdf>

NPS Fire Story, 2013: What happens after a tundra fire?
<http://www.nps.gov/fire/wildland-fire/connect/fire-stories/2013-parks/noatak-national-preserve.cfm>

Barnes, J.L, Barrett, C., Brown, T. and Hu, F.S. 2012. Tundra fires in northwestern Alaska: Impacts of burn severity on vegetation and soil carbon. (Presentation). AFE, Fire Ecology and Management Symposium. Portland, OR. December 2012.

Hu's Invited Oral Presentations that included results from this project:

2013 Seminar, Fujian Agriculture and Forestry University, Fuzhou, China
 2013 Seminar, Xiamen University, Xiamen, China
 2013 Seminar, Indiana State University, Terra Haute, IN
 2013 Seminar, East China Normal University, Shanghai, China
 2013 Lecture, Shanghai Jiaotong University, Shanghai, China
 2012 NSF Arctic LTER (Long-Term Ecological Research) Annual Meeting, Woods Hole, MA.
 2012 NSF PROBE Project Workshop "Fire Disturbance and Biogeochemical Cycles from Decadal to Millennial Timescales." Manhattan, KS
 2012 NIMBios Workshop "Disturbance Regimes and Climate-Carbon Feedback." National Institute for Mathematical and Biological Synthesis, Knoxville, TN
 2012 Seminar, Kyoto University, Kyoto, Japan
 2012 Seminar, Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan
 2011 Seminar, Northwestern University, Evanston, IL
 2011 Seminar, Toolik Lake Long-Term Ecological Research Station, AK
 2011 Seminar, Tsinghua University, Beijing, China
 2011 Seminar, Peking University, Beijing, China
 2010 American Geophysical Union, Biogeochemical Responses to Arctic Change, San Francisco, CA

Two manuscripts are under preparation based on the data, samples and results from this study. Noatak National Preserve, Alaska NPS Fire Management, and the Great Rivers CESU will be acknowledged in any peer-reviewed publication generated from this project.

All original paper data and photographs collected at the sites are currently housed and will be maintained by the Alaska Region, National Park Service office. Digital field data and summaries of lab results are also currently maintained at the Alaska Region, National Park Service office. Organic soil monolith material that remains after analyses will remain at the University of Illinois, Department of Biology Lab under Dr. Feng Sheng Hu.

References Cited

- Allen, J.L. & Sorbel, B. (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.
- Higuera, P.E., Chipman, M.L., Barnes, J.L., Urban, M.A. & Hu, F.S. (2011) Variability of tundra fire regimes in Arctic Alaska: Millennial-scale patterns and ecological implications. *Ecological Applications*, **21**, 3211-3226.
- Hu, F.S., Higuera, P.E., Walsh, J.E., Chapman, W.L., Duffy, P.A., Brubaker, L.B. *et al.* (2010) Tundra burning in Alaska: Linkages to climatic change and sea ice retreat. *Journal of Geophysical Research-Biogeosciences*, **115**, G04002.
- Key, C. & Benson, N.C. (2006) Landscape assessment: Ground measure of severity, the composite burn index; and remote sensing of severity, the normalized burn ratio. FIREMON: Fire Effects Monitoring and Inventory System. USDA Forest Service, Rocky Mountain Research Station- RMRS-GTR-164-CD: LA 1-51.
- Levin, I., Hammer, S., Kromer, B. & Meinhardt, F. (2008) Radiocarbon observations in atmospheric CO₂: Determining fossil fuel CO₂ over Europe using Jungfraujoch observations as background. *Science of the Total Environment*, **391**, 211-216.
- Mack, M.C., Bret-Harte, M.S., Hollingsworth, T.N., Jandt, R.R., Schuur, E.A.G., Shaver, G.R. *et al.* (2011) Carbon loss from an unprecedented Arctic tundra wildfire. *Nature*, **475**, 489-492.
- McGuire, A.D., Anderson, L.G., Christensen, T.R., Dallimore, S., Guo, L., Hayes, D.J. *et al.* (2009) Sensitivity of the carbon cycle in the Arctic to climate change. *Ecological Monographs*, **79**, 523-555.
- Oswald, W.W., Anderson, P.M., Brown, T.A., Brubaker, L.B., Hu, F.S., Lozhkin, A.V. *et al.* (2005) Effects of sample mass and macrofossil type on radiocarbon dating of arctic and boreal lake sediments. *Holocene*, **15**, 758-767.
- Racine, C.H., Dennis, J.G. & Patterson, W.A. (1985) Tundra fire regimes in the Noatak River Watershed, Alaska - 1956-83. *Arctic*, **38**, 194-200.
- Racine, C.H., Johnson, L.A. & Viereck, L.A. (1987) Patterns of vegetation recovery after tundra fires in Northwestern Alaska, USA. *Arctic and Alpine Research*, **19**, 461-469.
- Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G. *et al.* (2009) Intcal09 and Marine09 radiocarbon age calibration curves, 0-50,000 years cal bp. *Radiocarbon*, **51**, 1111-1150.
- Rocha, A.V., Loranty, M.M., Higuera, P.E., Mack, M.C., Hu, F.S., Jones, B.M. *et al.* (2012) The footprint of Alaskan tundra fires during the past half-century: Implications for surface properties and radiative forcing. *Environmental Research Letters*, **7**, 044039.

Rocha, A.V. & Shaver, G.R. (2011) Burn severity influences postfire CO₂ exchange in arctic tundra. *Ecological Applications*, **21**, 477-489.

Todd, S.K & Jewkes, H.A. (2006) Wildland fire in Alaska: A history of organized fire suppression and management in the last frontier. Agricultural and Forestry Experiment Station Bulletin No. 11. University of Alaska.

Wookey, P.A., Aerts, R., Bardgett, R.D., Baptist, F., Bråthen, K.A., Cornelissen, J.H.C. *et al.* (2009) Ecosystem feedbacks and cascade processes: Understanding their role in the responses of arctic and alpine ecosystems to environmental change. *Global Change Biology*, **15**, 1153-1172.

Yi, S. et al. (2010) A dynamic organic soil biogeochemical model for simulating the effects of wildfire on soil environmental conditions and carbon dynamics of black spruce forests. *Journal of Geophysical Research-Biogeosciences*, **115**, G04015.