

Estimating post-fire organic soil depth in the Alaskan boreal forest using the Normalized **Burn Ratio**

D. VERBYLA* and R. LORD

Bonanza Creek Long Term Ecological Research Program, University of Alaska,
Fairbanks, AK 99775-7200, USA

(Received 10 September 2006; in final form 11 November 2007)

As part of a long-term moose browse/fire severity study, we used the Normalized Burn Ratio (NBR) with historic Landsat Thematic Mapper (TM) imagery to estimate fire severity from a 1983 wildfire in interior Alaska. Fire severity was estimated in the field by measuring the depth of the organic soil at 57 sites during the summer of 2006. Sites were selected for field sampling from five fire severity classes based on threshold NBR values. The linear relationship between post-fire NBR and organic soil depth among sites within the burn was weak ($r^2=0.26$), and improved substantially ($r^2=0.66$) when restricted to non-wetland black spruce sites. The relationship between NBR and aspen/willow counts was non-linear. Sites with high densities of aspen stems consistently occurred in the high fire severity classes, and sites with high willow stem densities consistently occurred in the moderate fire severity class. However, NBR varied substantially from sites with low aspen or willow reproduction and therefore predicting aspen or willow regeneration based on post-fire NBR values would be difficult.

1. Introduction

The consumption of organic soil horizons by wildfire in boreal forests is a significant alteration that can influence post-fire permafrost dynamics, soil temperature and moisture (Yoshikawa *et al.* 2003), plant regeneration (Miyanishi and Johnson 2002, Wang 2003), and other physical and biological properties. Thus, post-fire residual organic soil depth is a key field measurement of fire severity in boreal forests.

Fire severity has been estimated using a variety of remotely sensed indices (White *et al.* 1996, Patterson and Yool 1998, Chuvieco *et al.* 2006, Miller and Thode 2007). The Normalized Burn Ratio (NBR) is a popular fire severity index used by land management agencies in the western USA (Kotliar *et al.* 2003, Howard and Lacasse 2004, Key and Benson 2005). This index typically responds to the substantial decrease in near-infrared reflectance (NIR) due to plant canopy damage (Chuvieco *et al.* 2006) and consumption by fire, and a substantial increase in shortwave infrared reflectance (SWIR) (White *et al.* 1996): $NBR = (NIR - SWIR) / (NIR + SWIR)$. If pre-fire imagery is available then the differenced NBR (dNBR) is often computed as the difference between pre- and post-fire NBR values.

Some studies have found a positive correlation between the NBR and visual field estimates of fire severity. In an evaluation of 13 fire severity indices, Epting *et al.* (2005) concluded that the NBR performed the best ($r^2=0.67, n=66$ plots, among

*Corresponding author. Email: D.Verbyla@uaf.edu

four burns) within closed-needleleaf forests in boreal Alaska. In a hyperspectral analysis of two forested burns in California, van Wagtendonk *et al.* (2004) found that an NIR band at 788 nm and an SWIR band at 2370 nm had the greatest changes following wildfire. They concluded that the NBR from hyperspectral Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) or broadband Enhanced Thematic Mapper Plus (ETM+) data should produce useful results in quantifying fire severity. Studies have found a strong relationship between NBR-based indices and a field-based Composite Burn Index (CBI in Arizona (Cocke *et al.* 2005, dNBR $r^2=0.84$, $n=92$ plots within one burn), Alaska (Sorbel and Allen 2005, dNBR $r^2=0.70$, $n=286$ plots among 10 burns) and California (van Wagtendonk *et al.* 2004, dNBR $r^2=0.89$, $n=63$ plots within one burn). However, other studies from California (Miller and Thode 2007, dNBR $r^2=0.49$, $n=741$ plots among 14 burns) and Alaska (Murphy *et al.* 2006, dNBR $r^2=0.08-0.64$, $n=39-70$ plots, five burns) have found the relationship between dNBR and fire severity to be weaker.

Roy *et al.* (2006) criticized the use of the NBR for fire severity mapping for several reasons. First, the NBR was originally used to map burned areas and not to estimate fire severity. Second, the NBR would be an optimal fire severity index if different levels of fire severity led to a spectral response perpendicular to NBR isolines and this was not the case. Third, field assessment of fire severity is often a qualitative visual value and not a quantitative measurement, and correlations between NBR and 'fire severity' may be due to factors other than fire severity.

This study was in support of a larger study examining the long-term impact of fire severity on moose browse production. Since the area burned in 1983, remote sensing estimates of fire severity from historic Landsat TM imagery was the only feasible method of mapping fire severity. We used the depth to mineral soil as a 2006 field measure related to fire severity. The depth of the organic soil horizon is a key variable controlling post-fire vegetation establishment with a mineral soil or shallow organic horizon required for successful germination and establishment of deciduous plant species (Johnstone and Kasischke 2005, Johnstone and Chapin 2006). The relationship between spectral reflectance and organic soil depth is not a direct relationship but is probably due to surface conditions following wildfire, such as uprooting and felling of black spruce stems due to the consumption of the organic horizon, or early colonization of deciduous plants varying with post-fire organic depth (Johnstone and Kasischke 2005, Johnstone and Chapin 2006).

Our objective in this study was to determine the relationship between the NBR and post-fire organic soil depth at several scales: within the entire burn, within two major pre-fire forest types, and within two classes of a black spruce forest type.

2. Study area

Our study area was the Rosy Creek Burn within the Bonanza Creek Long Term Ecological Research (LTER) site. The fire occurred in late June 1983 and covered over 2700 ha. Before the fire, the area was dominated by broadleaf aspen/birch and coniferous white spruce forest in the uplands, and black spruce forest and woodlands in the colder north-facing slopes and valley bottoms (Vioreck *et al.* 1983).

3. Methods

3.1 Image processing

We used the most recent cloud-free Landsat TM scene that was available after the 1983 fire. The 31 August 1985 scene was rectified to a 1-m 2005 digital orthophoto using an affine transformation based on 30 ground control points. The root mean squared error of the rectification model was 13m and the image was rectified using nearest-neighbour resampling as 25m pixels in UTM NAD83 Zone 6 projection. Spectral reflectances for the NIR and SWIR bands were computed using radiometric gain and bias values from each header file (Chander and Markham 2003). NBR values were then computed from TM band 4 (NIR) and band 7 (SWIR) reflectances. The mean NBR value within the burn perimeter was 0.29 with a standard deviation of 0.13. Based on these values, we segmented the burned area of the NBR image into five fire severity classes (table 1). Sixty-one plots were established in the centre of homogeneous patches from each fire severity class. The distance from plot location to patch edge was at least 100m. Our sampling concentrated on the classes with NBR values less than the mean NBR, as these represent more severely burned sites (Key and Benson 2005, Chuvieco *et al.* 2006).

3.2 Field methods

A hand-held Global Positioning System (GPS) receiver was used to navigate to each transect location. A 30-m north-south transect was established and soil pits were dug at the transect centre and at both ends of the transect. The depth of organic soil to mineral soil was measured at each soil pit to the nearest centimetre using a tape. It was not possible to determine the depth to mineral soil for six transects where frozen soil existed under deep organic soil, and in these six cases the depth to mineral soil was recorded as the depth to frozen soil. Site characteristics such as slope, aspect and vegetation type were recorded for each transect. In addition, counts of aspen and willow stems greater than 0.5m in height and within 1 m of the transect were recorded for each plot, representing important moose browse. The location of each transect centre was recorded using a GPS receiver. This location was later differentially corrected using GPS base station data. All spatial data were stored in the UTM NAD83 Zone 6 coordinate system.

All transects were established to be in the centre of homogeneous fire severity patches (table 1). After the GPS differential correction, three transects were excluded because they were not located more than 3 pixels from the edge of a fire severity

Table 1. Stratification of the 1983 Rosy Creek wildfire by 1985 NBR values. Lower NBR values typically correspond to high fire severity. The mean NBR value was 0.29 and the standard deviation was 0.13.

Class	NBR range	Number of sample plots
5	<0.03	14
4	0.03–0.15	14
3	0.16–0.41	22
2	0.42–0.55	9
1	>0.55	2
		Total=61 plots

patch. One other transect was also excluded because of a high variation of organic soil depth, ranging from 10 cm at one transect end to 51 cm at the other end.

Pre-fire vegetation of each plot was determined by visual interpretation of 1978 colour infrared photography. Pre-fire vegetation classes were aspen/birch (deciduous forest) or black spruce (coniferous forest/woodland).

4. Results and discussion

The linear relationship between the NBR and the mean depth of organic soil for all 57 transects was weak ($r^2=0.26$, $p<0.01$). The relationship was stronger among black spruce sites ($r^2=0.65$, $p<0.01$, $n=35$) and weaker among aspen/birch sites ($r^2=0.18$, $p=0.048$, $n=22$) (figure 1). The aspen/birch sites typically occurred on warmer and better-drained slope positions that probably had relatively shallow pre-fire organic horizon depths (Viereck *et al.* 1983, Ping *et al.* 2005, Harden *et al.* 2006), while all black spruce transects occurred on nearly level sites. The weaker correlation among aspen/birch sites might be due to relatively low pre-fire variation in organic horizon depth. The high variation of NBR among these sites could be due to topographic effects as the solar elevation was 33° during the satellite overpass, and the transects varied substantially in slope direction. The black spruce sites were classified in the field into wetland and non-wetland sites based on wetland/non-wetland vegetation. Non-wetland black spruce sites consisted of a woodland of black spruce trees with dominant understory shrubs of *Ledum* and *Vaccinium* species. Wetland black spruce sites consisted of a woodland of black spruce trees with a dominant understory of sedges (*Carex* spp.) and/or bog birch (*Betula nana*) shrubs. Among black spruce transects, the NBR/organic soil depth relationship was

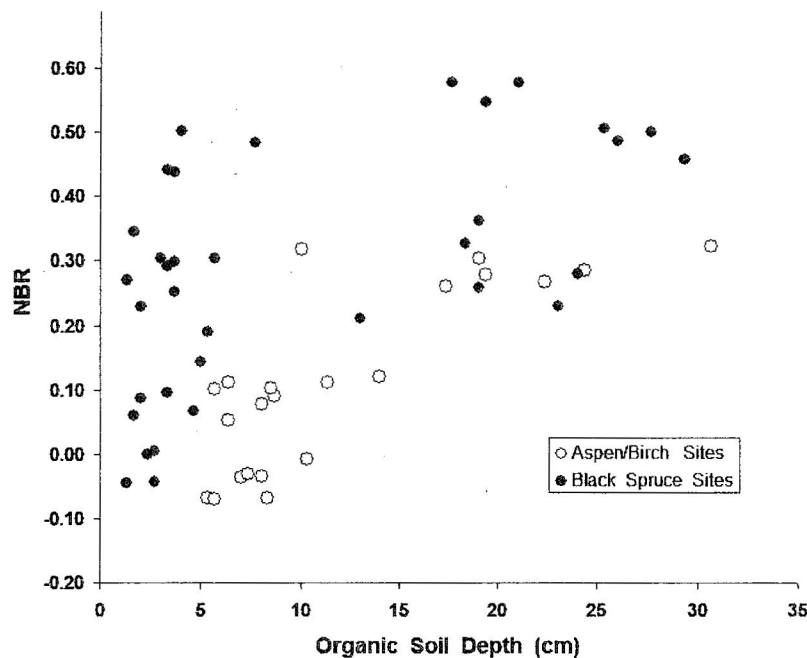


Figure 1. NBR and mean organic soil depth ($n=57$ transects, 22 aspen birch, 35 black spruce).

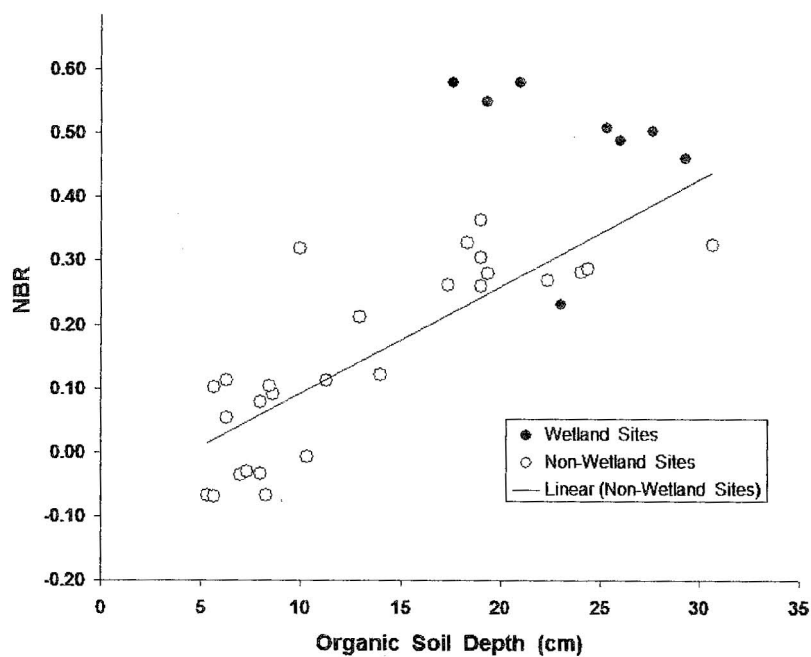


Figure 2. NBR and mean organic depth among wetland and non-wetland black spruce sites.

stronger among non-wetland sites ($r^2=0.66$, $p<0.01$, $n=27$) relative to transects from wetland sites ($r^2=0.08$, $p=0.48$, $n=8$) (figure 2). This is probably due to wetland sites not burning severely enough to consume organic soil (Swanson 1996).

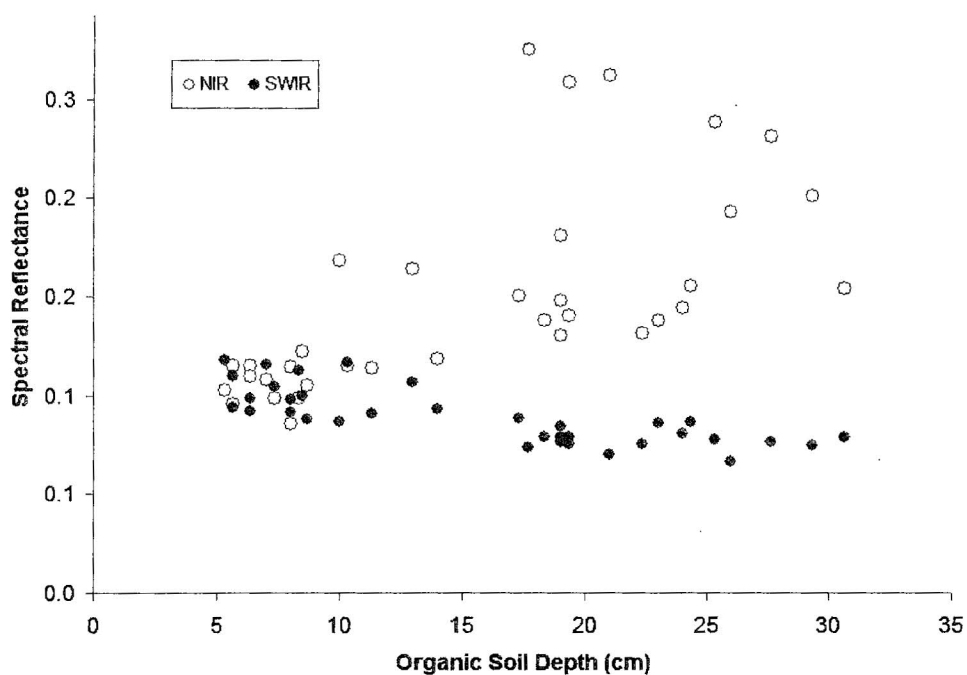


Figure 3. Post-fire NIR and SWIR reflectance and soil depth from black spruce sites.

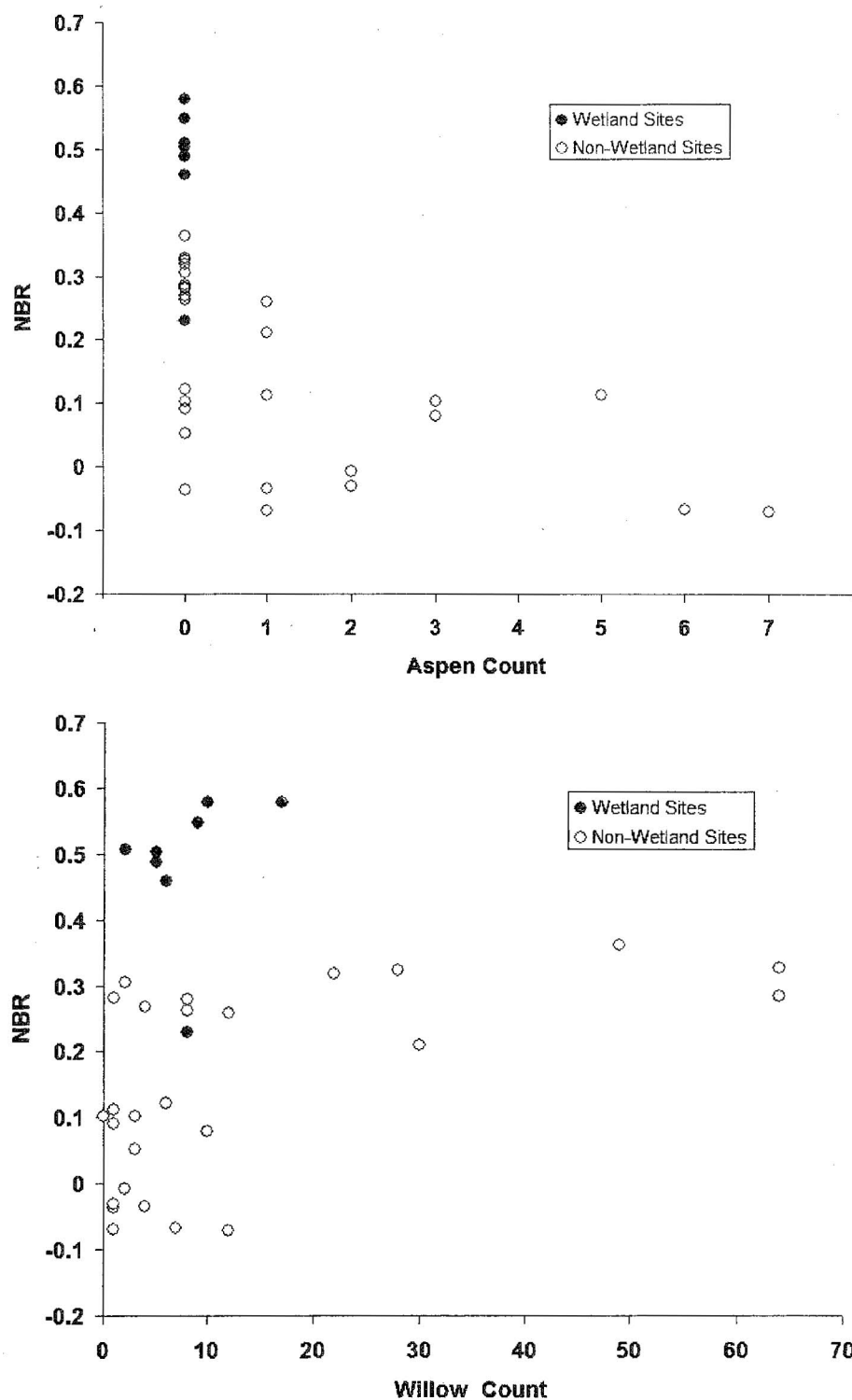


Figure 4. Frequency of aspen and willow stems in relation to post-fire NBR and organic soil depth.

Most of the wetland site had variable NBR values exceeding 0.4, probably due to variation in canopy conditions rather than fire severity at these wet sites.

The NBR in this study was from two growing seasons after the June fire. Thus, the spectral response may have been a combination of regenerating vegetation as well as post-fire charcoal and dead woody material. Black spruce sites that had shallow organic soil had relatively low NIR (figure 3), probably corresponding to low amounts of revegetation (Silva *et al.* 2004), and relatively high SWIR, probably corresponding to decreased shadowing (Nilson and Peterson 1994) or increased cellulose-lignin from exposure of dead twigs and branches (Daughtry 2001).

The main aim of this study was to map fire severity from historic Landsat TM data in an assessment of the long-term effect of fire severity on moose browse such as willow shrubs and aspen saplings. Sites with low NBR values had the highest density of aspen stems, whereas sites with an aspen count of zero had the highest variation in NBR (figure 4), probably related to post-fire organic soil depth (Johnstone and Chapin 2006). For example, none of the deep organic soil, wetland black spruce transects had aspen, while there was a high variation in aspen density among transects with shallow organic soils. Sites with moderate NBR values had the highest density of willow stems (figure 4), probably related to post-fire organic soil depth, as shallow organic sites consistently had low willow densities.

5. Conclusions

The post-fire spectral response of the NBR was weakly related to organic soil depth if applied to all transects from the burn. This weak relationship was most probably due to vegetation type and topography influencing the post-fire spectral response and masking the spectral response related to fire severity. There was a stronger linear relationship between post-fire NBR and organic soil depth when vegetation type was restricted to non-wetland black spruce sites. The relationship between the NBR 2 years after the fire and aspen/willow density over 20 years post-fire was confounded by high variation in NBR values at sites with low aspen/willow densities.

Acknowledgements

Funding for this project was provided by the Bonanza Creek Long Term Ecological Research Program (funded jointly by NSF grant DEB-0423442 and USDA Forest Service, Pacific Northwest Research Station grant PNW01-JV11261952-231). Data from this research are archived and available through the BNZ-LTER website www.lter.uaf.edu/data.cfm.

References

- OIANDER, G. and MARKHAM, B., 2003, Revised Landsat-5 TM radiometric calibration procedures and postcalibration dynamic ranges. *IEEE Transactions on Geoscience and Remote Sensing*, 41, pp. 2674-2677.
- OILIVIECO, E., RIANNO, D., DANSON, F.M. and MARTIN, P., 2006, Use of a radiative transfer model to simulate the postfire spectral response to burn severity. *Journal of Geophysical Research*, 111, pp. 1-15.
- COCKE, A.E., FULE, P.Z. and CROUSE, J.E. 2005, Comparison of burn severity assessments using differenced Normalized Burn Ratio and ground data. *International Journal of Wildland Fire*, 14, pp. 189-198.
- DALIGHTR Y, CS.T., 2001, Discriminating crop residues from soil by shortwave infrared reflectance. *Agronomy Journal*, 93, pp. 125-131.

- EPTING, J., VERBYLA, D. and 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**, pp. 328-339.
- HARDEN, J.W., MANIES, K.L., TURETSKY, M.R. and NEFF, J.C., 2006, Effects of wildfire and permafrost on soil organic matter and soil climate in interior Alaska. *Global Change Biology*, **12**, pp. 2391-2403.
- HOWARD, S.M. and LACASSE, J.M., 2004, An evaluation of gap-filled Landsat SLC-off imagery for wildland burn severity mapping. *Photogrammetric Engineering and Remote Sensing*, **70**, pp. 877-880.
- JOHNSTONE, J.P. and CHAPIN, F.S. III., 2006, Effects of soil burn severity on post-fire tree recruitment in boreal forest. *Ecosystems*, **9**, pp. 14-31.
- JOHNSTONE, J.F. and KASISCHKE, E.S., 2005, Stand-level effects of soil burn severity on postfire regeneration in a recently burned black spruce forest. *Canadian journal of Forest Research*, **35**, pp. 2151-2163.
- KEY, C.H. and BENSON, N., 2005, Landscape assessment: ground measure of severity: the composite burn index, and remote sensing of severity, the normalized burn ratio. In *FIREMON: Fire Effects Monitoring and inventory System*, USDA Forest Service General Technical Report RMS-GTR-164, pp. LA1-LA51. [I]
- KOTLIAR, N.B., HAIRE, S.L. and KEY, C.H., 2003, Lessons from the fires of 2000: post-fire heterogeneity in ponderosa pine forests. USDA Forest Service Proceedings RMRS-P-29, pp. 277-280. [g]
- MILLER, J.D. and THODE, A.E., 2007, Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment*, **109**, pp. 66-80.
- MIYANISHI, K. and JOHNSON, E.A., 2002, Process and patterns of duff consumption in the mixedwood boreal forest. *Canadian journal of Forest Research*, **32**, pp. 1285-1295.
- MURPHY, K.A., REYNOLDS, J.H. and KOLTUN, J., 2006, How well does the national burn severity mapping methodology work on national wildlife refuge lands in Alaska? [II]
- NILSON, T. and PETERSON, U., 1994, Age dependence of forest reflectance: analysis of main driving factors. *Remote Sensing of Environment*, **48**, pp. 319-331.
- PATTERSON, M.W. and YOOI, S.R., 1998, Mapping fire-induced vegetation mortality using Landsat Thematic Mapper data: a comparison of linear transformation techniques. *Remote Sensing of Environment*, **65**, pp. 132-142.
- PING, CL., MICAELSON, GJ., PACKEE, E.C., STILES, CA., SWANSON, O.K. and YOSHIKAWA, K., 2005, Soil catena sequences and fire ecology in the boreal forest of Alaska. *Soil Science Society of America journal*, **69**, pp. 1761-1772.
- RoY, D.P., BOSCHETTI, L. and TRIGG, S.N., 2006, Remote sensing of fire severity: assessing the performance of the Normalized Burn Ratio. *IEEE Geoscience and Remote Sensing Letters*, **3**, pp. 112-116.
- SILVA, J.M.N., CADIMA, J.F.CL., PEREIRA, J.M.C. and GREGOIRE, J.M., 2004, Assessing the feasibility of a global model for multi-temporal burned area mapping using SPOT-VEGETATION data. *International journal of Remote Sensing*, **25**, pp. 4889-4913.
- SORBEL, B. and ALLEN, J., 2005, Space-based burn severity mapping in Alaska's national parks. *Alaska Park Science*, **4**, pp. 4-11.
- SWANSON, D., 1996, Susceptibility of permafrost soils to deep thaw after forest fires in interior Alaska, USA, and some ecologic implications. *Arctic and Alpine Research*, **28**, pp. 217-227.
- VANWAGTENDONK, J.W., ROOT, R.R. and KEY, CC., 2004, Comparison of AVIRIS and Landsat ETM+ detection capabilities for burn severity. *Remote Sensing of Environment*, **92**, pp. 397-408.
- VIERECK, L.A., DYRNESS, CT., VANCLEVE, K. and FOOTE, MJ., 1983, Vegetation, soils, and forest productivity in selected forest types of interior Alaska. *Canadian Journal of Forest Research*, **13**, pp. 703-720.

- WANG, G.G., 2003, Early regeneration and growth dynamics of *Populus tremuloides* suckers in relation to fire severity. *Canadian journal of Forest Research*, 33, pp. 1998-2006.
- WHITE, J.O., RYAN, K.C., KEY, C.C. and RUNNING, S.W., 1996, Remote sensing of forest fire severity and vegetation recovery. *International journal of Wildland Fire*, 6, pp. 125-136.
- YOSHIKAWA, K., BOLTON, W.R., ROMANOVSKY, V.E., FUKUDA, M. and HINZMAN, M., 2003, [±] Impacts of wildfire on the permafrost in the boreal forests of interior Alaska. *Journal of Geophysical Research*, 108, D1:8148.