MODIS-informed greenness responses to daytime land surface temperature fluctuations and wildfire disturbances in the Alaskan Yukon River Basin

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Pronounced climate warming and increased wildfire disturbances are known to modify forest composition and control the evolution of the boreal ecosystem over the Yukon River Basin (YRB) in interior Alaska. In this study, we evaluate the post-fire green-up rate using the normalized difference vegetation index (NDVI) derived from 250 m 7 day eMODIS (an alternative and application-ready type of Moderate Resolution Imaging Spectroradiometer (MODIS) data) acquired between 2000 and 2009. Our analyses indicate measurable effects on NDVI values from vegetation type, burn severity, post-fire time, and climatic variables. The NDVI observations from both fire scars and unburned areas across the Alaskan YRB showed a tendency of an earlier start to the growing season (GS); the annual variations in NDVI were significantly correlated to daytime land surface temperature (LST) fluctuations; and the rate of post-fire green-up depended mainly on burn severity and the time of post-fire succession. The higher average NDVI values for the study period in the fire scars than in the unburned areas between 1950 and 2000 suggest that wildfires enhance post-fire greenness due to an increase in post-fire evergreen and deciduous species components.

1. Introduction

Since the 1990s, Alaska, especially its interior, has become a focus for global change studies because of its extreme environments, increased wildfire events, and high sensitivity to land surface disturbances (Epting and Verbyla 2005; Allen et al. 2006; Riordan, Verbyla, and Mcguire 2006; Allen and Sorbel 2008; Barrett et al. 2011; Turetsky et al. 2011). The extreme conditions related to high latitudes, such as limited sunlight, low temperature and permafrost, short growing season (GS), persistent clouds, and snow cover on the ground, make it difficult for scientists to acquire reliable and real-time characterization of its land surface. Satellite observations of the land surface characteristics provide an approach to

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understanding the Alaskan ecosystems and their responses to global warming and increased wildfire disturbances.

The normalized difference vegetation index (NDVI) has proved to be a key identifier for the dynamics of vegetation structure and function (Riaño et al. 2002; Jia, Epstein, and Walker 2006) and has become the most widely used tool for assessing post-fire vegetation succession at the landscape scale (Kushla and Ripple 1998; Viedma and Meliá 1999; Goetz et al. 2005; Goetz and Bunn 2006; Murphy, Reynolds, and Koltun 2008; Gouveia, Dacamara, and Trigo 2010). GS NDVI is also thought to be a reasonable proxy for biomass production (Xia., Huang, and Han 2005) or gross primary productivity (Wylie et al. 2008), because it is not dependent on plant species (Abdel-Malak and Pausas 2006).

The Moderate Resolution Imaging Spectroradiometer (MODIS) acquires data over the entire Earth’s surface in nearly daily intervals, and its products are generated in multiple spatial resolutions. Because of the frequent repeat cycle, MODIS can fill in scattered cloudy days, capture phenological changes (Reed et al. 2009), and identify land surface changes more frequently than Landsat. MODIS’s spatial resolution of 250–1000 m allows more detailed observations than its predecessor, the Advanced Very High Resolution Radiometer (AVHRR).

However, MODIS vegetation products are constrained to programmatic standards for compositing interval, map projection, and file format that hinder their usability in operational monitoring activities. This is especially true in high-latitude regions where short phenological cycles and geometric distortion are inherently problematic (Khlopenkov and Trishchenko 2008; Luo, Trishchenko, and Khlopenkov 2008; Ji et al. 2010). In areas such as Alaska, where snow can melt and flora emerge overnight, the compositing interval and delivery latency of the standard MODIS NDVI products probably lead to missed opportunities for relevant observations, and properly processed remotely sensed products may have more chances to catch such a phenomenon. A recent alternative, which preserves the best qualities of MODIS data and delivers them as applications-ready products, is called eMODIS (Jenkerson, Maiersperger, and Schmidt 2010). Comparing it with standard MODIS and Advanced Spaceborne Thermal Emission and Reflection (ASTER) data, Ji et al. (2010) commented that eMODIS Alaska products show significant improvements in geometric features because they are mapped directly from the original swath data and preserve the original MODIS spectral characteristics.

The MODIS vegetation index products include NDVI and the enhanced vegetation index (EVI) (Huete et al. 2002). The NDVI is one of most common spectral vegetation indices and widely applied for tracking vegetation dynamics, especially suitable for areas with a relative low density of biomass (Ji and Peters 2007), such as Alaskan boreal ecosystems where NDVI values are usually less than 0.72 as indicated by our data sets. On the other hand, EVI retains sensitivity to vegetation dynamics at a high biomass level whose NDVI saturation likely occurs (Huete et al. 2002; Ji and Peters 2007). Moreover, no EVI products are available at the 250 m resolution. Finally, the time-series eMODIS NDVI data are available for such a huge area without cost and delivered in a user-friendly format (geo tiffs) with an Alaska-centric Albers Equal Area projection. Therefore, the 250 m MODIS NDVI was used in this study to evaluate greenness responses to wildfires in the Alaskan Yukon River Basin (YRB) from 2000 to 2009. Our specific objectives are

1. to illustrate temporal and spatial variations of GS mean NDVI over the Alaskan YRB;
2. to demonstrate the post-fire green-up in relation to daytime land surface temperature (LST) fluctuations and burn severity classes; and
3. to characterize the long- and short-term post-fire successions.
2. Materials and methods

2.1. Study areas

The Alaskan YRB (Figure 1) covers an area of 502,451 km². About 35% of the region experienced wildfires between 1950 and 2007. Fire scars from significant events in 2004 and 1999 were used to evaluate post-fire vegetation successions in this study. The 1999 fire scars sum to 3717 km². The wildfire events in 2004, the largest fire disturbances since 1950, resulted in a total burned area of 26,500 km². The spatial distributions of both years’ fire scars are illustrated in Figure 1.

According to the burn severity data provided by the Monitoring Trends in Burn Severity Project at the U.S. Geological Survey Earth Resources Observation and Science (USGS EROS) Center (Eidenshink et al. 2007), of all fire scars in 2004, 12% were classified as high burn severity, 37% as moderate burn severity, 28% as low burn severity, and 23% as unburned area (Tan et al. 2007).

The Beaver Creek region (see Figure 1) was selected for the pilot study to determine how the green-up rate for specific fire years is associated with post-fire succession type and burn severity. Beaver Creek covers an area of 20,928 km², in which evergreen forests account for 59%, shrublands for 29%, and wetlands for 9% (2001 National Land Cover Database, NLCD). Our ground observations show that the flat portions of the Beaver Creek are mostly dominated by white spruce (*Picea glauca*) and black spruce (*Picea mariana*), along with numerous deciduous (e.g. birch and aspen) and mixed forests. The cumulative percentage of the burned area within the Beaver Creek between 1950 and 2007 was 43%.

2.2. eMODIS NDVI

The eMODIS 7 day enhanced maximum-value composite NDVI images at 250 m resolution from 2000 through 2009 were downloaded from http://dds.cr.usgs.gov/emodis/Alaska.

![Figure 1](image-url)  
*Figure 1. YRB in Alaska, the Beaver Creek region (BC), and the distribution of fire scars from 1999 and 2004. The 1999 and 2004 fire scars account for 0.7% and 5.3%, respectively, of the total area of the basin.*
Jenkerson, Maiersperger, and Schmidt (2010) documented the details regarding eMODIS products and their generation. In this study, we used a composite to represent each eMODIS 7 day enhanced maximum-value composite NDVI image.

We defined the GS in interior Alaska as starting at the beginning of April and ending at the end of September (Wylie, Zhang, and Bliss 2008) and represented it with 26 7 day composites. The GS was defined on the basis of NDVI values that were \( \geq 0.09 \) (Jia, Epstein, and Walker 2006). The NDVI data presented in this article were rescaled from the original range of 0–1 to the range of 0–100. Any values less than 9 were considered to indicate snow cover before the start of the GS. A time-series smoothing technique developed by Swets et al. (1999) was used to smooth the eMODIS NDVI composites, in which a weighted least-square linear regression approach corrected poor-quality observations resulting from clouds or other atmospheric contamination. For the smoothing technique to perform successfully, the composites were extended by five composites prior to the start of the GS and five composites after its end by replicating the adjacent composite within the season.

2.3. Burn severity data
The burn severity data were derived from http://www.mtbs.gov/compositfire/mosaic/bin-release/download.html. The data sets were generated by the Monitoring Trends in Burn Severity Project at USGS EROS (Eidenshink et al. 2007), in which the approach proposed by Key (2006) was used for classifying burn severity and mapping. The details about the generation of burn severity classes and validation can be found at http://www.mtbs.gov/methods.html.

2.4. Historical fire scars and land-use/land-cover data
Historical fire scars (fire perimeters) data from 1950 through 2006 over the Alaskan YRB were obtained from http://agdc.usgs.gov/data/blm/fire/firehistory/akfirehist06_metadata.htm and the data from 2007 to 2009 were obtained from http://agdc.usgs.gov/data/blm/fire/index.html.

The 2001 NLCD for Alaska was obtained from http://www.mrlc.gov/nlcd01_data.php and used to define the land-cover types of pre-fires.

2.5. LSTs and precipitation
We used MOD11A2 8 day 1000 m grid daytime LST to compute weekly and monthly mean LSTs and their maximum and minimum LSTs for the period of 2000–2008. The MOD11A2 daytime LST data were downloaded from the Land Processes Distributed Active Archive Center (LPDAAC, https://lpdaac.usgs.gov/products/modis_products_table). From this data set, we extracted and processed the daytime LST to obtain the LST in degrees Celsius for the study. Therefore, the maximum and minimum temperatures used here refer only to daytime maximum and minimum temperatures. The precipitation data, produced by McKenney et al. (2006) from the Canadian Forest Service, are available at http://cfs.nrcan.gc.ca/projects/3/3.

2.6. Data analysis
The composites were masked by the regions of interest (e.g. the Alaskan YRB, Beaver Creek, and their fire scars in 1999 and 2004). The mean NDVI values within the masked
areas for each composite were calculated on a pixel-by-pixel basis with the Environmental Systems Research Institute’s (ESRI’s) ArcGIS. Thus, all NDVI values presented in this article are area-weighted. GS cumulative NDVI is just a sum of the mean values of all composites within a year. During the GS as defined above, there are about 26 composites (weekly eMODIS from the first week of April to the last week of September) every year, but only the composites with NDVI values of 9 or higher are qualified for analyses. Therefore, the number of composites involved in any calculations (e.g. the GS mean NDVI and the standard deviation) could vary from year to year.

The mean NDVI values for all qualified composites within the GS were computed to illustrate the interannual variations in the GS mean NDVI across the Alaskan YRB from 2000 to 2009 (Objective 1).

We also computed the 1000 m NDVI (in order to match the 1000 m grid daytime LST) to demonstrate the annual variations in mean and maximum GS NDVI (1000 m) from 2000 to 2009 as related to daytime LST fluctuations over the 1999 fire scars across the Alaskan YRB; then identified how post-fire composite NDVI from wildfire disturbances was related to the daytime LSTs and burn severity classes (Objective 2).

To characterize the long- and short-term post-fire successions (Objective 3), we classified all lands into fire scars and unburned areas from 1950 through 2007 over the Alaskan YRB based on the historical fire scars database as described above. Then, we computed the GS mean NDVI for the fire scars for the period of 1950–2000 as the long-term successions and for the period of 2001–2007 as short-term successions. Similarly, we calculated the GS mean NDVI for the unburned areas for the period of 1950–2007. Finally, we normalized the GS mean NDVI of fire scars using the GS mean NDVI of unburned areas for each respective period, and generated graphs for comparisons.

3. Results and discussion

3.1. Composite NDVI and interannual variations over the Alaskan YRB

The mean composite NDVI for April–May and for the GS and the GS cumulative NDVI averaged over the whole Alaskan YRB are presented in Table 1. There were spatially explicit patterns and annual variability in the GS NDVI from 2000 to 2009 over the study area (see Figure 2). Generally, GS NDVI tended to increase over the study period (Table 1), while the annual variations almost responded to the daytime LST fluctuations, especially to the daytime minimum temperature (see Section 3.2). According to a National Oceanic and Atmospheric Administration (NOAA) report on 19 January 2012

<table>
<thead>
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<th>Year</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
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<td>28</td>
<td>24</td>
<td>27</td>
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<tr>
<td>Stdev</td>
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<td>8</td>
<td>14</td>
<td>9</td>
<td>11</td>
<td>12</td>
<td>12</td>
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<td>48</td>
<td>46</td>
<td>48</td>
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<td>46</td>
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<tr>
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<td>14</td>
<td>14</td>
<td>16</td>
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<td>15</td>
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<tr>
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<td>893</td>
<td>1039</td>
<td>1061</td>
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Notes: GS, growing season starting from the beginning of April to the end of September in general, but varying year to year, depending on when the first composite has an NDVI value of ≥ 9. All values are area-weighted and on a 0–100 scale. Stdev: standard deviation.
Figure 2. Spatial patterns of the growing season (GS) mean NDVI (250 m NDVI on a 0–100 scale) across the Alaskan YRB and their interannual variations from 2000 to 2009.

(http://www.noaanews.noaa.gov/stories2012/20120119_global_stats.html), a long-term temperature increase of about 0.12°F (0.07°C) per decade since 1895 in the USA was mainly due to the increase in air minimum temperature. That could be related to the increasing trend of the daytime LSTs.

When the composite NDVI value of 9 was used to define as a proxy for a start of the GS in the Alaskan YRB (Jia, Epstein, and Walker 2006), each GS for the study period tended to start earlier and last longer. For example, the starting date of the GS was in the first week of May for 2000, 2001, 2002, and 2006; in the fourth week of April for 2004, 2008, and 2009; in the third week of April for 2005; and in the second week of April for 2003 and 2007. Regardless of any stage of a GS, the annual incremental trend followed a polynomial track. Using NDVI, Kaduk and Los (2011) projected an advance of green-up by 4–15 days in northern middle and high latitudes over the period of 2000–2060. And Tang and Zhuang (2011) attributed an expansion trend of the GS in Alaskan boreal forest ecosystems to an increase in snow-free days. Using both AVHRR and Landsat, Pouliot, Latifovic, and Olthof (2009) revealed an increasing NDVI trend over the northern regions of Canada from 1986 to 2006.
3.2. **NDVI uncertainty in relation to daytime LST variations**

The GS mean NDVI (1000 m resolution) and daytime LSTs (minimum and maximum) during the GS over the 1999 fire scars are summarized in Figure 3. There was a pronounced increasing trend in the daytime LST, especially the daytime minimum temperature, from 2000 to 2008, which contributed to the earlier start of the GS. Marked temperature drops occurred in 2006 and 2008, which coincided with the decreases in NDVI (Figure 3). The interannual variation in mean daytime temperatures over the 2004 fire scars showed a similar pattern (not shown here). The lowest NDVI value over the 2004 fire scars occurred in 2005, which can be mainly attributed to the destruction of well-established vegetation communities by the previous year’s wildfire disturbances. In comparison with the 1999 fire scars, the immediate green-up rate was higher in the 2004 fire scars.

Generally, the green-up following wildfire disturbances in the Alaskan YRB boreal ecosystem can be influenced by LSTs. As illustrated in Figure 4(a), the 1000 m NDVI was significantly linearly correlated to the monthly mean daytime minimum temperature (coefficient of determination, $R^2 = 0.90$) and to the monthly mean daytime maximum temperature over the 1999 fire scars ($R^2 = 0.80$). Similar correlations were also observed for the entire Alaskan YRB (including both fire scars and unburned areas). Examining such relations at a composite (weekly) time step, the NDVI response to the maximum temperature before the end of July can be better described by a logarithmic equation as illustrated in Figure 4(b). This graph also indicates that when the daytime minimum temperature was lower than 0°C, the NDVI was more sensitive to variations in temperature. Reed et al. (2009) noted that snowmelt, the start date of a GS, and the green-up rate are mainly related to the magnitude of and variation in the minimum temperature. Furthermore, this sensitivity was present until the end of July, regardless of whether the area had been affected by fires.

There were significant interannual variations in precipitation over the fire scars in the Alaskan YRB, but there was no consistent increasing or decreasing trend over time, which appears to differ from an increasing trend over the last century for the entire

![Figure 3](image-url)  
**Figure 3.** Growing season (GS) mean and maximum NDVI (1000 m NDVI on a 0–100 scale) over the 1999 fire scars from 2000 to 2009 in relation to annual variations in LSTs during the GS within the 1999 fire scars over the Alaskan YRB. The interannual variations in NDVI appear to coincide with the fluctuations of daytime LSTs during the study period.
Figure 4. Relationships of mean NDVI (on 0–100 scale) to land surface temperatures between 2000 and 2008 over the 1999 fire scars within the Alaskan YRB. (a) Monthly mean NDVI from April to September; (b) weekly NDVI from the beginning of April to the end of July. Note: $T_{\text{min}}$ and $T_{\text{max}}$ refers to the minimum and maximum daytime temperatures, respectively.

3.3. Impacts of burn severity on greenness and post-fire successions

According to the Wildland Fire Dataset for Alaska (available at http://agdc.usgs.gov/data/blm/fire/index.html), of the land areas in the 2004 fire scars in Beaver Creek region, 5.6%, 32.6%, and 31.3% of the area was estimated as being in the high, moderate, and low burn severity classes, respectively, and 30.5% in the unburn class. As illustrated by Figure 5(a), wildfires had significant negative impacts on NDVI for the first several years following a fire, but burn severity levels could make big differences in longer-term ecological impacts. Compared to those in the pre-fire year 2003, the largest decrease in the GS mean NDVI was found in 2005 (the first year post-fire): 26%, 24%, 20%, and 14% for high, moderate, low burn severity classes, and unburned areas, respectively. The post-fire NDVI magnitudes were differentiated by burn severity classes. By relating a remotely sensed (Landsat TM) burn severity index and pre-fire- and post-fire vegetation responses to burn severity classes within a 1986 fire in interior Alaska, Epting and Verbyla (2005) presented a similar result that the highest NDVI occurred within the fire scars classified as the highest burn severity. Our results as illustrated in Figure 5(b) also suggest a critical influence of burn severity on post-fire successions, which appears to be prolonged (see more discussion in Section 3.4). By integrating MODIS NDVI into a data-driven model to evaluate climatic influences on Alaskan boreal forest regeneration from fires, Wylie, Zhang, and Bliss (2008) found that the areas with lower greenness are usually associated with recent fires or insect infestation,
whereas the higher greenness is present in older fire scars where increased deciduous vegetation components are expected. For example, fires with high burn severity greatly reduce the thickness of organic matter layer (Kasischke et al. 2010) and likely lead to long-term deciduous forest communities (Barrett et al. 2011). In fact, the pronounced interannual variation could have resulted from weather and other biophysical variables as suggested by Wylie, Zhang, and Bliss (2008).

3.4. Long- and short-term post-fire successions

As illustrated in Figure 6(a), the GS NDVI values from 2000 to 2009 were significantly and consistently higher (by an average of 8% ranging from 5% in 2002 to 9% in 2008) in the fire scars of the areas burned between 1950 and 2000 than in the unburned areas. This is despite the significant and consistently lower NDVI values caused by fire events. In order to exclude the effects of other factors such as variations in climate, location, and other biophysical variables, our original NDVI values were normalized against the unburned areas (see Figure 6(b)). In Figure 6(b), the difference in NDVI between both old fire scars and unburned areas could be attributed to the role of wildfires in stimulating generation and/or regeneration of some vegetation species. Compared to the unburned areas, the fire scars had 4.5% more evergreen forest area and 1.8% more deciduous forest but 6% less mixed forest area based on the 2001 NLCD. It has been reported that post-fire successions (Rupp, Chapin, and Starfield 2000; Goulden et al. 2006) and climate change (Kronberg and

Figure 5. (a) Pre-fire growing season (GS) mean NDVI (250 m NDVI on a 0–100 scale) and the post-fire recovery of the 2004 fire scars in relation to burn severity classes in the Beaver Creek region and (b) growing season (GS) mean NDVI has been normalized with the NDVI under the burn severity class “Unburn” from graph (a).
Figure 6. (a) Annual variations in growing season (GS) mean NDVI (250 m NDVI on a 0–100 scale) within the fire scars for the periods of 1950–2000 and 2001–2007, and within the unburned areas for the period of 1950–2007 over the Alaskan YRB and (b) the GS mean NDVI within the fire scars has been normalized with the NDVI of the unburned areas from graph (a).

Watt 2000; Calef et al. 2005) likely increase the deciduous components of boreal forests such as aspen, birch, and poplar (Wylie, Zhang, and Bliss 2008). Barrett et al. (2011) found that potential shifts in dominant forest cover in interior Alaska are driven by variations in burn severity and organic layer thickness. Epting and Verbyla (2005) observed that the self-replacement appeared to dominate post-fire successions in interior Alaska: pre-fire needle-leaf forest mostly succeeds to needle-leaf woodland and pre-fire broadleaf forest likely succeeds to broadleaf shrubland.

The NDVI magnitude depends on the duration of time between fires, tending to become higher over time after each fire event. At a decade’s interval, the average NDVI estimated over the Alaskan YRB was 46, 47, 46, 45, 43, and 42 for the fire scars in the 1950s, 1960s, 1970s, 1980s, 1990s, and 2000s, respectively. In other words, post-fire green-up rate increases over time and it may take about 50 years for fire scars to reach the maximum greenness in the region. This conclusion was also noted by Chen et al. (2003) and Goulden et al. (2006). But much shorter periods of post-fire successions, ranging from 9 years to 25 years, were also documented by other studies (e.g. Epting and Verbyla 2005; Wylie, Zhang, and Bliss 2008). In fact, the time for post-fire green-up could vary largely due to differences in burn severity, dominant succession vegetation, and biogeophysical settings.

4. Conclusion

The eMODIS-derived NDVI values over burned and unburned areas in the Alaskan YRB from 2000 to 2009 indicate a tendency of an earlier start to GS and significant correlations between the mean NDVI magnitudes and the daytime LSTs. The post-fire green-up rate
depends mainly on burn severity and the time since a fire event. Our results suggest that wildfires can enhance greenness. The maximum greenness may occur about 50 years after fire disturbances (e.g. fires in the 1960s) in the Alaskan YRB, but the time could vary greatly with the burn severity class, the type of succession vegetation communities, and other biophysical conditions. Knowledge of the green-up of fire scars and its association with post-fire succession types may be useful for both scientists and land managers to understand the ecological impacts of wildfires and potential effects of climate change over the Alaskan YRB.

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