Browning of the landscape of interior Alaska based on 1986-2009 Landsat sensor NDVI

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Abstract: We used a time series of 1986–2009 Landsat sensor data to compute the Normalized Difference Vegetation Index (NDVI) for 30 m pixels within the Bonanza Creek Experimental Forest of interior Alaska. Based on simple linear regression, we found significant ($p < 0.05$) declining trends in mean NDVI of three dominant landscape types of floodplains, lowlands, and uplands. At smaller patch sizes, similar declining trends occurred among topographic classes of north- and south-facing slopes and valley bottoms and among forest classes, including black spruce (*Picea mariana* (Mill.) B.S.P.). Significant positive trends in mean NDVI occurred only in areas that were recently burned, whereas wetlands had no significant trend. The greatest departure from the NDVI trend line occurred following the 2004 drought for all forest classes except black spruce, which dominates the coldest sites, and balsam poplar (*Populus balsamifera* L.), which occurs on low, moist terraces within the Tanana River floodplain. The consistent long-term declining trend at several spatial scales may be due to a regional climatic regime shift that occurred in the mid-1970s.

Résumé : Dans une perspective circumpolaire boréale, l'intérieur de l'Alaska est un point chaud de la baisse de productivité de la végétation et de la tendance au brunissement selon l'indice de végétation par différence normalisée (IVDN) obtenu par la télédétection. Du point de vue de l'Alaska, plusieurs études ont montré que la tendance au brunissement était plus prononcée dans la région boréale orientale, ce qui en Alaska est cohérant avec un gradient climatique d'ouest en est. Cependant, on possède peu d'information au sujet de la variation à l'échelle du paysage de la baisse de l'IVDN à des échelles spatiales plus fines (c.-à-d., 1 ha ou moins). Nous avons utilisé des séries temporelles du capteur de l'IVDN de Landsat de 1986 à 2009 pour étudier l'évolution de l'IVDN parmi une hiérarchie spatiale de classes de paysage, de topographie et de végétation à la forêt expérimentale de Bonanza Creek à l'intérieur de l'Alaska. En utilisant une régression linéaire simple, nous avons trouvé des tendances à la baisse significatives ($p < 0,05$) de l'IVDN moyen de trois types dominants de paysage de plaine inondable, de basses terres et de hautes terres. À l'échelle de plus petites parcelles de terrain, des tendances similaires à la baisse sont apparues parmi les classes topographiques des pentes exposées au nord et au sud et du fond des vallées, ainsi que des classes de forêt incluant l'épicéa noir (*Picea mariana* (Mill.) Britton, Sterns, Poggenb.). Des tendances positives significatives de l'IVDN moyen ont été observées seulement dans les zones récemment brûlées tandis que les zones humides n'étaient associées à aucune tendance significative. L'écart le plus important de la courbe d'évolution de l'IVDN est survenu à la suite de la sécheresse de 2004 dans toutes les classes de forêt à l'exception de l'épicéa noir qui domine dans les stations les plus froides et du peuplier baumier (*Populus balsamifera* L.) qui croît sur les terrasses basses et humides dans la plaine inondable de la rivière Tanana. La tendance à la baisse constante à long terme à plusieurs échelles spatiales pourrait être due à un changement dans le régime du climat régional qui est survenu au milieu des années 1970.

[Traduit par la Rédaction]

Introduction

High-latitude biomes are currently experiencing warming faster than most locations on earth (Arctic Council and the International Arctic Science Committee (IASC) 2005). In boreal Alaska, warming since the 1950s has been unprecedented in at least the last 400 years (Barber et al. 2004; Kaufman et al. 2009), and over the last 50 years, average annual temperature in this region has increased 2.2 °C (Stafford et al. 2000). The effects of climate change in boreal Alaska have occurred and are expected to continue as a result of high-latitude amplification (Shulski and Wendler 2007; Walsh et al. 2008). For example, over the past 100 years, the unfrozen season length in interior Alaska has increased by 45% with no significant increase in precipitation (Wendler and Shulski 2009). In a region where growing season precipitation can be less than 150 mm, a warming climate can lead to major changes in boreal ecosystems (Chapin et al. 2006; Soja et al. 2007; Wolken et al. 2011).

The remotely sensed Normalized Differenced Vegetation Index (NDVI) is a time series of data that can be used to monitor changes in boreal vegetation (Pettorelli et al. 2005). The NDVI can range from −1.0 to +1.0, where negative values correspond to unvegetated surfaces and forested surfaces typically have NDVI values exceeding 0.4 at the peak of the growing season. NDVI contrasts the reflectance between the

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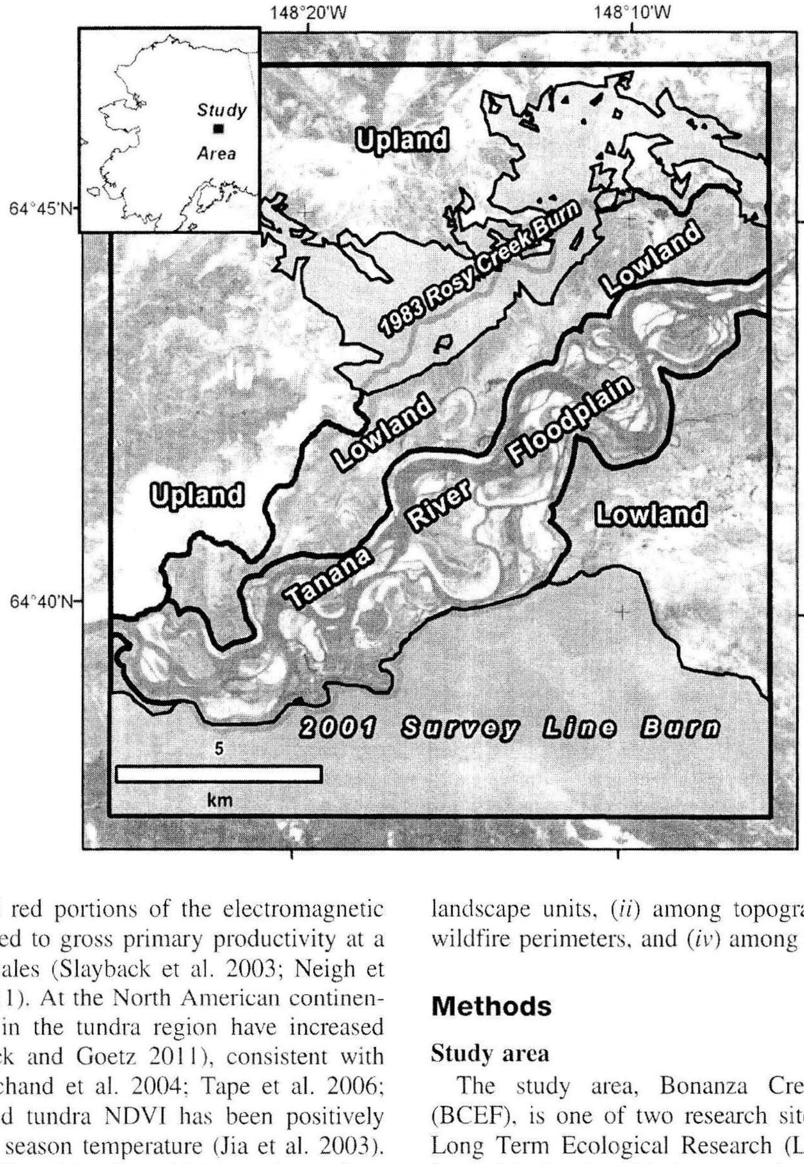
Fig. 1. Landscape units used for analysis. Background is 2001 Landsat TM near-infrared band 4 image.



near infrared (NIR) and red portions of the electromagnetic spectrum and is correlated to gross primary productivity at a wide range of spatial scales (Slayback et al. 2003; Neigh et al. 2008; Beck et al. 2011). At the North American continental scale, NDVI trends in the tundra region have increased (Goetz et al. 2005; Beck and Goetz 2011), consistent with field observations (Marchand et al. 2004; Tape et al. 2006; Walker et al. 2006), and tundra NDVI has been positively correlated with growing season temperature (Jia et al. 2003). In contrast, in areas unaffected by fire within interior regions of boreal North America, the NDVI trend has been negative (Goetz et al. 2005), with this "browning trend" expanding in recent years (Beck and Goetz 2011). In boreal Alaska, the trend of declining NDVI is strongest in the eastern boreal region, consistent with a west to east climatic gradient (Verbyla 2008; Parent and Verbyla 2010). This browning pattern is consistent with tree-ring measurements across the boreal region of Alaska, with declining forest productivity occurring in regions where mean growing season temperature exceeds 12 °C (Beck et al. 2011). However, there is little information about the landscape-level variation in declining NDVI at finer spatial scales (i.e., 1 ha or less).

Within the region of declining NDVI, what forest types and landscape positions are contributing to this browning trend? A time series of NDVI derived from Landsat sensors allows for analysis at a finer spatial scale (30 m pixels) located within the "browning boreal region" of Alaska. In this study, we investigated 1986–2009 NDVI trends at a variety of scales including (*i*) among floodplain, lowland, and upland landscape units, (*ii*) among topographic classes, (*iii*) within wildfire perimeters, and (*iv*) among vegetation classes.

Methods

Study area

The study area, Bonanza Creek Experimental Forest (BCEF), is one of two research sites of the Bonanza Creek Long Term Ecological Research (LTER) program. BCEF is located in interior Alaska approximately 20 km southwest of Fairbanks and encompasses over 5000 ha. This area is a representative cross section of boreal landscapes including lowlands, the floodplain of the glacially fed Tanana River, and a variety of boreal vegetation types in the upland landscape (Fig. 1).

Interior Alaska is bounded to the south by the Alaska Range and to the north by the Brooks Range. The region has a continental climate with a mean annual temperature of −2.2 °C and a mean annual precipitation of approximately 280 mm (Hammond and Yarie 1996; Wendler and Shulski 2009). Average growing season length is 123 days, an increase of 45% over the past century (Wendler and Shulski 2009). The mean May–August temperature is 13.5 °C, well above the 12 °C threshold at which regional declining NDVI and declining tree-ring growth has occurred (Beck et al. 2011).

Soil development in the region, which was unglaciated during the last glacial maximum, varies depending on landscape position. Permafrost is intermittent throughout the

Table 1. Landsat scenes used for analysis.

Year	Date	Satellite and sensor	Path/row	Cloud masking
1986	1 July	Landsat 5-TM	70/15	No
1991	22 June	Landsat 5-TM	69/15	No
1995	11 August	Landsat 5-TM	70/15	No
1999	19 June	Landsat 5-TM	70/15	Yes
2000	16 August	Landsat 7-ETM+	70/15	No
2001	16 June	Landsat 7-ETM+	70/15	No
2002	6 August	Landsat 7-ETM+	70/15	No
2003	10 August	Landsat 5-TM	69/15	No
2006	9 August	Landsat 5-TM	70/15	No
2008	20 June	Landsat 5-TM	69/15	Yes
2009	30 June	Landsat 5-TM	70/15	Yes

Note: Any clouds in imagery were masked to eliminate cloud effects on NDVI analysis.

study area. In the uplands, permafrost is common on north-facing slopes and in valley bottoms. In lowland and floodplain landscapes, permafrost is controlled by subsurface water flow and the presence or absence of an insulating moss layer (Hinzman et al. 2006). Most of the soils in the uplands are alluvial deposits from the Tanana River, whereas the lowland soils often have a thick organic horizon over loess due to colder temperatures and poor drainage (Ping et al. 2006). In the Tanana River floodplain, the soils are the result of alluvial deposition resulting in salt-affected soils due to the glacial sediments and evaporation of shallow groundwater (Van Cleve et al. 1996). Soil moisture on the Tanana River floodplain can be influenced by river level as there is a close relationship between river stage, groundwater level, and soil moisture (Viereck et al. 1993). Because the main source of the Tanana River is glaciers from the Alaska Range, there is a positive correlation of July–August discharge with air temperature (Nossov et al. 2010).

Fire is the dominant landscape disturbance in interior Alaska, and there have been two fires at BCEF in the past 30 years (Fig. 1). In 1983, the Rosie Creek fire burned 3400 ha, burning both lowland and upland landscapes. The Survey Line fire in 2001 burned over 6000 ha in the Tanana River floodplain and lowlands. Both fires were human-caused and started in June.

Processing Landsat sensor data

In this study, we used 30 m pixel imagery to determine NDVI trends as they relate to topography, vegetation, and disturbance regime. The Landsat images were downloaded from the U.S. Geological Survey (USGS) Web site (http://glovis.usgs.gov/) and the Global Land Cover Facility (GLCF) Web site (http://www.landcover.org). Landsat TM and ETM+ images (Table 1) were chosen based on the following criteria: (*i*) they were all from 20 June to 16 August, when interior Alaska forests are phenologically similar in terms of seasonal peak NDVI (Parent and Verbyla 2010), and (*ii*) they were all relatively cloud-free.

Landsat sensor images were co-registered to a Landsat sensor GeoCover orthorectified image from 16 August 2000 in the UTM projected coordinate system (zone 6, WGS84). A minimum of 30 ground control points were used in co-registering each image, and each linear co-registration model had an RMS positional error of less than 15 m (0.5 pixels). Nearest-neighbor sampling was used during the co-registration to retain the original pixel spectral values. All output pixels were 30 m × 30 m.

After co-registration, pixel values were converted to at-sensor spectral reflectance using methods described in Chander et al. (2009). Spectral reflectance values were normalized for variable atmospheric conditions using a radiometric regression method (Hall et al. 1991). Forty unvegetated pseudo-invariant features, 20 bright and 20 dark, were used to develop regression models to normalize spectral reflectance values to the base image from 11 August 1995. The dark features were pixels from near the center of 20 nonturbid lakes and ponds, and the bright features were pixels from 20 unvegetated surfaces such as alluvial gravel or sand bars or gravel pits, and the center pixels were from highways. In each case, the coefficient of determination was >0.95, and both red and NIR spectral reflectances were radiometrically adjusted using this method. NDVI was then computed for each vegetated pixel using the adjusted spectral reflectances. Nonvegetated pixels and clouds were then excluded using two techniques: (*i*) by excluding all pixels with an NDVI value less than or equal to 0.3, and (*ii*) by masking out cold cloud pixels using the thermal band of the Landsat images. The mean NDVI from each area class (landscape unit (uplands, lowlands, floodplain), topographic classes, burn areas, and vegetation classes) was computed for each image year. We then used linear regression of mean NDVI from 1986 to 2009 (n = 11 years) to determine trends within each area class. We did not apply any topographic-illumination corrections because we stratified by topographic classes in the uplands, and the landscape units of lowlands and flooplains were flat.

Classifying landscape units

The landscape was divided in a spatial hierarchy to determine NDVI trends first across the entire Bonanza Creek Experimental Forest (BCEF) study area, then at successively smaller spatial scales of landscape units, and topographic units, and finally by vegetation type. Due to the large area affected by fire, we also investigated the NDVI response of both a 1983 and a 2001 burn within BCEF.

We classified BCEF into the three landscape units of uplands, lowlands, and active floodplain (Fig. 1). The uplands were defined using a National Elevation Dataset (http://ned.usgs.gov) 2 arc second digital elevation raster that was projected to UTM 30 m pixels. Ten metre contour lines were

Table 2. Vegetation classes used for analysis of NDVI trends.

Vegetation class	Pixels	Hectares	Polygons
Black spruce	7602		62
Acidic black spruce	3307	1357	11
Non-acidic black spruce	3150	1202	41
Deciduous	2647		97
Quaking aspen	680	345	7
Balsam poplar	722	280	62
Alaska birch forest	940	438	8
Mixed forest	7581		71
Upland mixed forest	6670	2783	21
Floodplain mixed forest	678	293	41
White spruce	4976		73
Upland white spruce	1689	688	11
Floodplain white spruce	3124	1261	62
Wetland	1572		71
Scrub wetland	207	82	16
Open wetland	1360	540	55

Note: Black spruce, *Picea mariana* (Mill.) B.S.P.; quaking aspen, *Populus tremuloides* Michx.; balsam poplar, *Populus balsamifera* L.; Alaska birch, *Betula neoalaskana* Sarg.; white spruce, *Picea glauca* (Moench) Voss.

computed, and the uplands were defined using the contour line at the base of slopes. The active floodplain was defined using a combination of a 200 m buffer around the Tanana River and the low-elevation contours. Finally, the lowland was defined as the remaining areas not classified as uplands or active floodplain.

The uplands were further classified into topographic units. The north- and south-facing uplands classes were based on aspect, with slope direction between 315° and 45° defined as north-facing and slope direction between 135° and 225° defined as south-facing. Finally, the valley bottoms in the uplands were defined based on slope gradient and distance from stream channel (Nagel 2007).

Burn polygons were mapped from postfire satellite images. An outline of the Rosie Creek burn was created from a 24 June 1983 Landsat 4 MSS, path 69 row 15 image. This Landsat scene was chosen as it was acquired days after the fire was extinguished . A threshold of NIR band values was used to map burned from unburned areas, and the resulting polygons were verified with later years of higher resolution imagery. The outline of the 2001 Survey Line burn was derived from the U.S. Bureau of Land Management's Wildland Fire Dataset for Alaska (http://fire.ak.blm.gov/predsvcs/maps.php) and interpretation of the imagery acquired shortly after the fire.

For analysis of NDVI trends in different vegetation classes (Table 2), we used a polygon-based vegetation map of the area (http://www.lter.uaf.edu/gis/gis_data.cfm). The map was produced based on a floristic classification using data from 85 field sites from 2009–2010, resulting in 12 vegetation classes (Baird 2011). Black spruce (*Picea mariana* (Mill.) B.S.P.) classification was guided by Hollingsworth et al. (2006) where acidic and non-acidic black spruce communities differ mainly in drainage, with well-drained sites typically being non-acidic. Vegetation polygons were delineated based on landscape position and color and texture characteristics of 2003–2007 high-resolution color infrared imagery (Baird 2011).

Computing NDVI trends

We used simple linear regression of mean NDVI values from each spatial class (landscape units, burn perimeters, topographic and vegetation classes) over the 23-year period. In 2004, interior Alaska experienced record warm and dry conditions leading to severe drought (Fig. 2). Due primarily to smoke and cloud contamination, there were no acceptable Landsat images of the area available from 2004 or 2005. We examined 2006 NDVI regression residuals as postdrought departure from the trend line by vegetation class.

Results

NDVI trends across the study area by landscape position and topographic class

The entire study area and each of the landscape units (uplands, lowlands, and floodplain) had significant negative trends in NDVI. The lowlands landscape unit had a stronger declining trend relative to the uplands or floodplain landscape units (Table 3). NDVI was consistently higher in the uplands than in both the lowlands and floodplain (Fig. 3*a*), most likely due to the higher proportion of broadleaf stands in the uplands. In 2000, relative to the trend lines, there was a relatively higher mean NDVI across all landscape units (Fig. 3*a*). Within the unburned upland landscape, north- and south-facing slopes and upland valley bottoms had significant negative trends in NDVI . The north-facing slopes and bottomland classes had a stronger declining NDVI trend relative to the south-facing slopes class (Table 3). The higher NDVI values on south-facing slopes compared with north-facing slopes (Fig. 3*b*) is most likely due to a higher proportion of broadleaf deciduous stands on south-facing slopes.

NDVI trends within burned areas

NDVI consistently increased in burned areas following fire. The 1983 Rosie Creek burn area showed a significant increasing trend in NDVI for 17 years postfire NDVI until 2000 (Fig. 4). The Survey Line area and the adjacent lowlands had similar and significant 1986–2000 negative trends

Fig. 2. Mean summer (June through August) temperature versus total precipitation, Fairbanks, Alaska, USA. The warmest summer on record was in 2004, and based on dendrochronology, it was the warmest summer in the past 200 years (Barber et al. 2004).

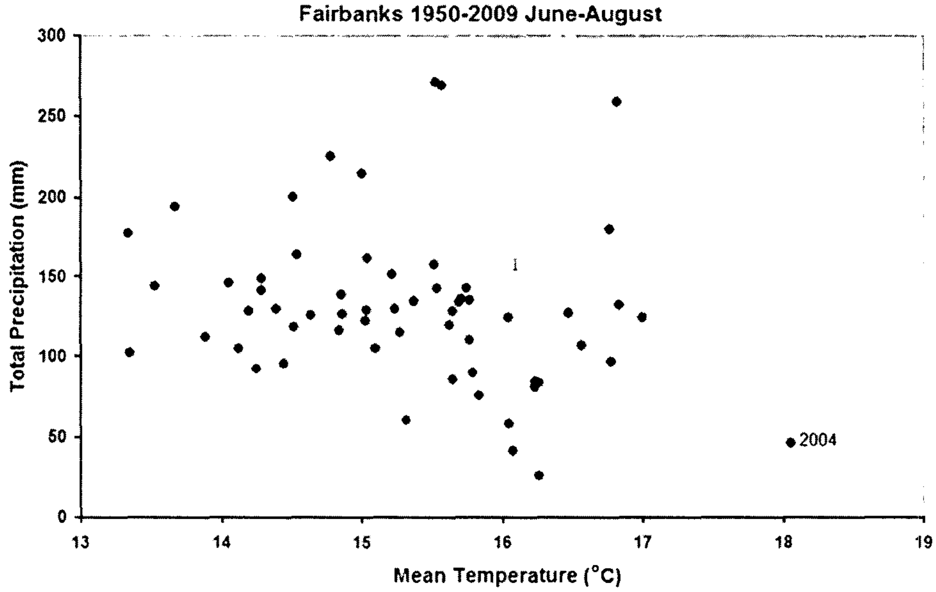


Table 3. Linear regressions for 1986–2009 based on mean NDVI within each area (n = 11 years).

Area (excluding burns)	Pixel count	r^2	Slope	p value
BCEF study area	135 263	0.75	–0.0029	0.001
Uplands	64 378	0.65	–0.0027	0.003
Lowlands	64 331	0.75	–0.0034	0.001
Floodplain	24 328	0.62	–0.0028	0.004
North-facing slopes	22 424	0.74	–0.0030	0.001
South-facing slopes	26 735	0.55	–0.0027	0.009
Valley bottoms	18 799	0.72	–0.0031	0.001
Rosie Creek burn	21 552	0.60	0.0026	0.005
Survey Line burn	45 005	0.53	–0.0059	0.011

in NDVI prior to the 2001 fire. Following the 2001 fire, the burned area had an increasing NDVI trend (Fig. 4) until 2009, when the area burned had a similar mean NDVI as the adjacent unburned lowlands.

NDVI trends by vegetation type

All four major forest types had significant negative trends in mean NDVI, whereas wetland types had no significant trends (Table 4). Black spruce had the most significant declining trend among the major forest types. The quaking aspen (*Populus tremuloides* Michx.; aspen hereafter) NDVI trend was significant if the 1986 low NDVI anomaly (Fig. 5) was excluded from the time series. We did exclude 1986 from the aspen NDVI time series, as 1986 was a year of high defoliation by aspen tortrix (*Choristoneura conflictana*) (Werner 2010). Floodplain mixed forest and floodplain balsam poplar (*Populus balsamifera* L.) classes had the strongest declining NDVI trends. White spruce (*Picea glauca* (Moench) Voss) and mixed forest vegetation types had stronger declining NDVI trends within the floodplain relative to uplands (Table 4). In the uplands, upland mixed forest and Alaska birch (*Betula neoalaskana* Sarg.; birch hereafter) has stronger declining NDVI trends relative to white spruce.

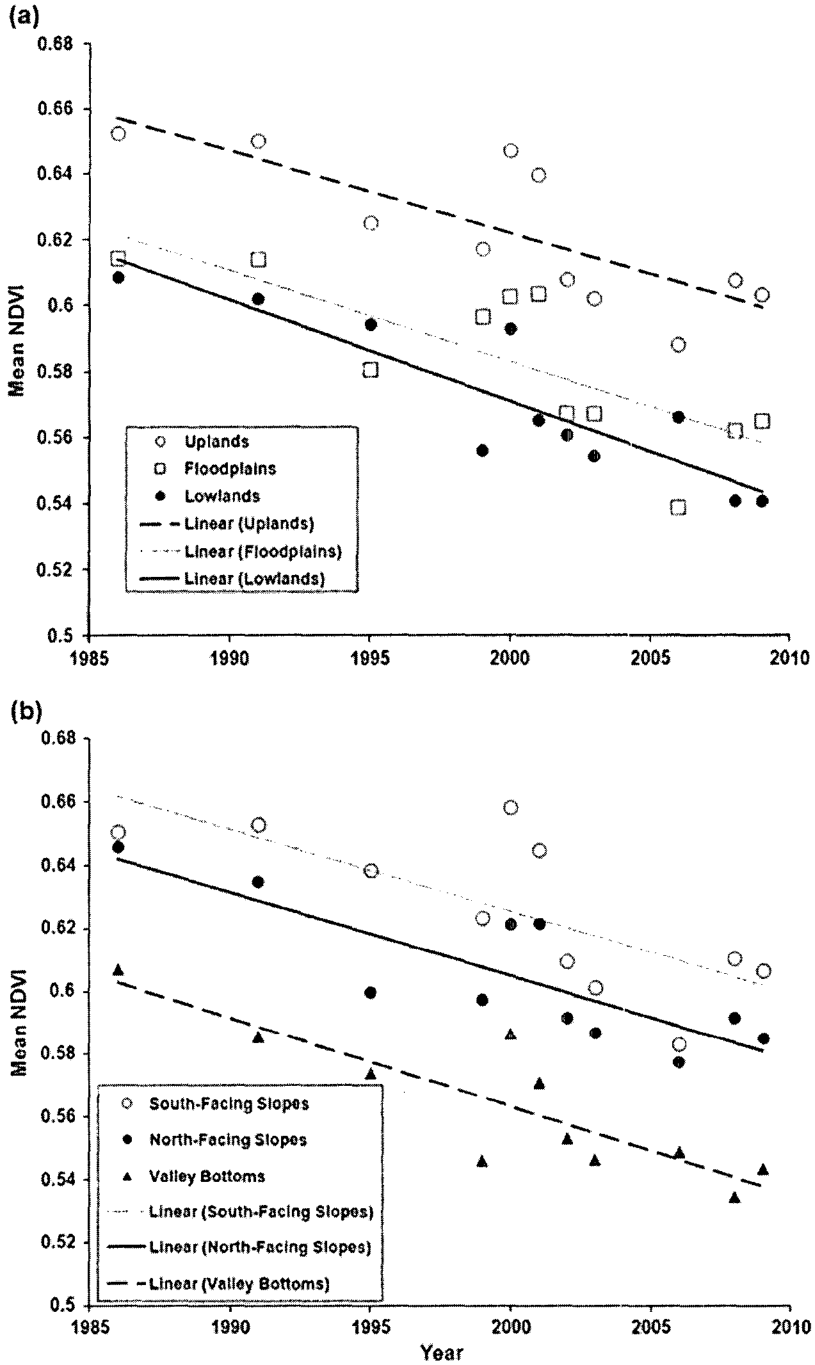
Most vegetation types had similar interannual NDVI patterns (Table 5), with the exception of aspen because of the extreme low NDVI value in 1986 associated with defoliation by the aspen tortix. Non-acidic and acidic black spruce had the strongest correlation (r = 0.98), and the correlation between white spruce and black spruce types was weaker (r < 0.75). The greatest departure from the NDVI trend line for each vegetation class was in 2006 for all vegetation classes except black spruce and balsam poplar classes (Fig. 6)

Discussion

Based on regional studies (Verbyla 2008; Parent and Verbyla 2010; Beck et al. 2011), it is clear that NDVI has declined in interior Alaska boreal vegetations over the past two to three decades. To understand some of the underlying physical and biological factors correlated with regional declining NDVI, we examined changes in NDVI at a finer spatial scale.

We expected the declining NDVI trends to occur primarily on relatively warm, dry sites and within certain vegetation types such as white spruce; however, we found a similar negative trend in NDVI in the three landscape units, in different topographic classes, and in forested vegetation classes. This is likely due to the dominant effect of regional climate warm-

Fig. 3. The 1986–2009 trend in mean NDVI values within the study area (excluding burned pixels) (n = 11 years) by (a) landscape position and (b) unburned upland south- and north-facing slopes.



ing, leading to declining NDVI across topographic and vegetation classes. Nearby Fairbanks is relatively warm and dry, with 1986–2009 June–August mean temperature of 15.7 °C and mean total precipitation of 137 mm (http://climate.gi.alaska.edu/). Based on analysis of tree rings and carbon isotope data from the study region, the warmest summers in the past 200 years have occurred in the period since the mid-1970s (Barber et al. 2004). With warmer temperatures and no significant trend in precipitation, an increase in potential evapotranspiration has occurred in boreal Alaska (Riordan et al. 2006; Beck et al. 2011).

Tree-ring studies from across boreal Alaska and western Canada have suggested temperature-induced growth decreases in trees. D'Arrigo et al. (2004) found that the optimal summer temperature for white spruce growth in the Yukon Territory had been consistently exceeded since the 1970s. Within our study area, declining growth trends associated with recent warming have been documented in upland white spruce (Barber et al. 2000), upland black spruce (Juday et al. 2005), and lowland black spruce (Wilmking and Myers-Smith 2008). Similar results have been documented across eastern boreal Alaska and the Yukon Territory. For example,

Fig. 4. The 1986–2009 trend in mean NDVI within the 1983 Rosie Creek burn area and the 2001 Survey Line burn area (n = 11 years).

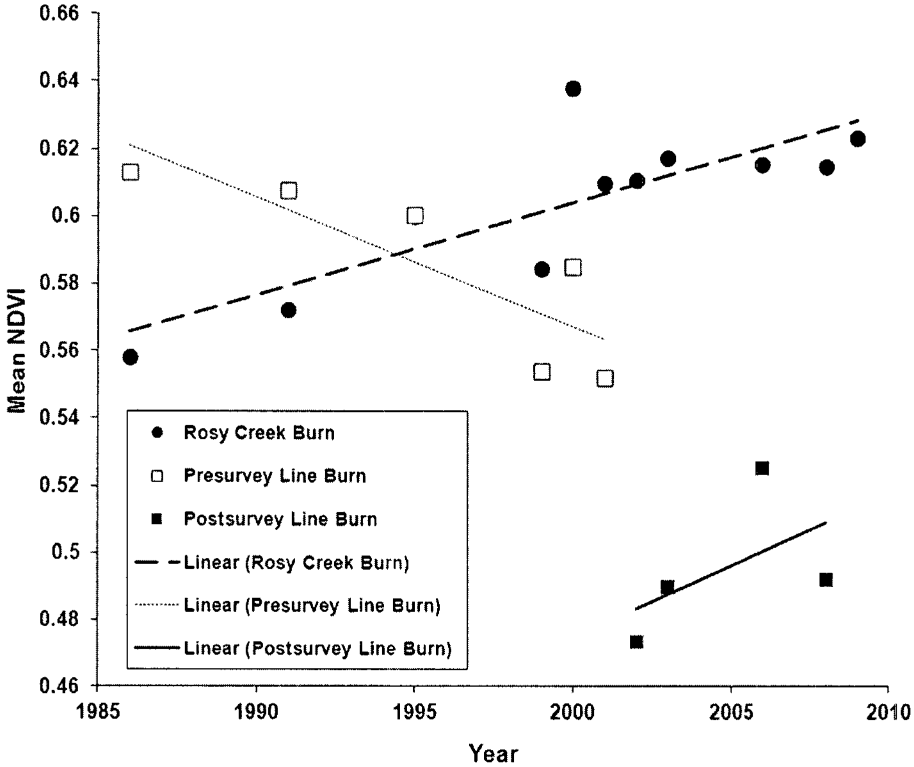


Table 4. 1986–2009 mean NDVI linear regression trends by vegetation class subsample area (n = 11 years).

Vegetation type	Pixel count	r^2	Slope	p value
Black spruce	32 068	0.78	–0.0030	0.000
Acidic black spruce	14 450	0.75	–0.0030	0.001
Non-acidic black spruce	13 214	0.72	–0.0028	0.001
Deciduous	13 002	0.42	–0.0030	0.032
Quaking aspen*	3 806	0.49	–0.0007	0.024
Balsam poplar	3 054	0.79	–0.0037	0.000
Alaska birch forest	4 854	0.59	–0.0029	0.013
Mixed forest	35 047	0.64	–0.0031	0.003
Upland mixed forest	31 514	0.61	–0.0030	0.004
Floodplain mixed forest	3 121	0.73	–0.0045	0.001
White spruce	21 073	0.46	–0.0029	0.022
Upland white spruce	7 632	0.28	–0.0019	0.094
Floodplain white spruce	13 441	0.53	–0.0036	0.011
Wetland	6 837	0.23	–0.0020	0.132
Scrub wetland	913	0.36	–0.0021	0.051
Open wetland	5 924	0.22	–0.0019	0.148

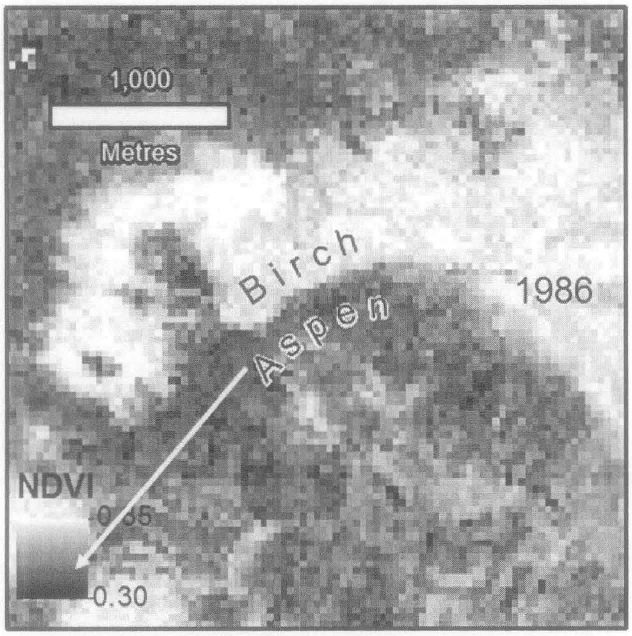
Note: See Table 2 for full species names.

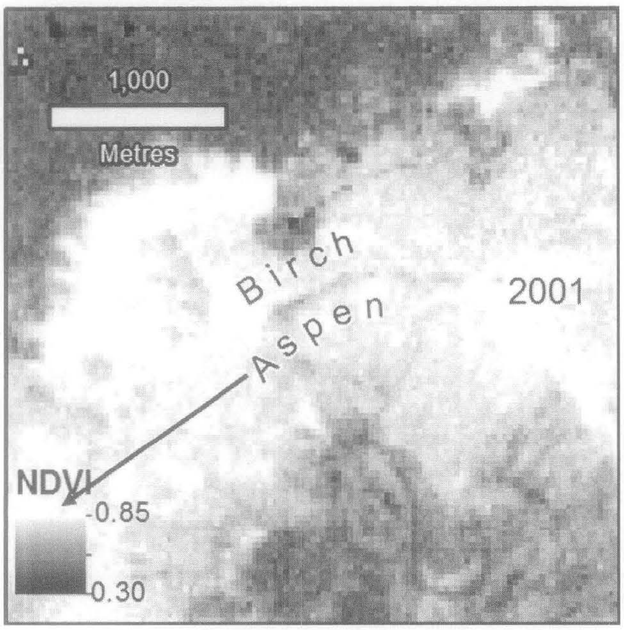
*The 1986 NDVI for the aspen class was excluded from the regression due to an infestation of aspen tortrix (*Choristoneura conflictana*) defoliating most aspen stands in 1986.

Hogg and Wein (2005) found decreased tree-ring growth in both aspen and white spruce associated with decreases in precipitation among 12 mature stands in river valleys of southwestern Yukon; these stands had strong declining growth trends since the mid-1990s. Beck et al. (2011) reported a drought-induced shift in tree-ring isotopic composition since the 1980s in black and white spruce and associated decreases in productivity in upland and floodplain sites across interior Alaska. At lower elevations, Beck et al. (2011) found that eight of the 10 wettest sites, based on a topographic index, had declining NDVI and spruce tree-ring growth rates. Lloyd and Fastie (2002) found that after 1950, warmer temperatures were associated with decreased tree growth in seven of eight cold sites in three boreal regions of Alaska; only the wettest region had increased growth associated with warmer temperatures.

Fertilization and moisture exclusion studies at plots within our study area (Yarie and Van Cleve 2010) have shown that

Fig. 5. The 1986 and 2001 NDVI from adjacent quaking aspen (*Populus tremuloides*) and Alaska birch (*Betula neoalaskana*) stands. In 1986, aspen stands in our study area were defoliated by the aspen tortrix (*Choristoneura conflictana*) (Werner 2010).





moisture is now the primary factory limiting production of most forest vegetation types. In the uplands landscape, growth of white spruce or birch was insensitive to fertilization, whereas thinning increased growth, likely due to reduced competition for soil moisture. Based on an 18-year rainfall-exclusion experiment (McGuire et al. 2010), white spruce tree growth on the floodplain was more sensitive to summer precipitation relative to upland sites. This may be due to a shallower rooting depth on floodplain sites relative to upland sites (Yarie and Van Cleve 2010). Our results of white spruce and mixed forest vegetation classes having stronger declining NDVI trends within the floodplain relative to uplands landscape may also reflect a greater sensitivity to drought on the floodplain landscape.

Succession following disturbance was likely the dominant process controlling increases in NDVI within the burned areas and early succession floodplain communities. The postfire recovery of mean NDVI varied by burn area: 17 years for the upland Rosie Creek burn and 9 years for the lowland Survey Line burn. This was likely due to differences in prefire vegetation and site moisture, as well as fire severity (Bernhardt et al. 2011).

The only vegetation types that did not show a significant trend in NDVI were wetland classes (Table 4). This was likely due to interannual variability of surface water and wetland herbaceous plant phenology. The mean NDVI in wetland classes was consistently lower in June relative to the adjacent year's August (Fig. 7), likely due to greater surface water and lower leaf area in June relative to August. Wetland types are also less likely to be drought-stressed relative to forest vegetation types.

In general, there were similar interannual variations in NDVI among vegetation classes (Table 5). Mean NDVI had a high departure from the trend line in the year 2000 for all landscape positions, topographic classes, and most vegetation classes. This may have been due to a relatively wet growing season during 1998. Other wet growing seasons of 1990, 2003, and 2008 were not followed by similar increases in NDVI, likely due to drought in 1991, 2004, and 2009 (Fig. 8). We also saw a large departure from the mean NDVI for aspen in 1986 (Fig. 5). This low NDVI value in 1986 was due to the infestation of a defoliator insect, the aspen tortrix (Werner 2010).

Most forest types had the greatest departure below the trend line in 2006 following the 2004 drought. Despite having the most significant long-term declining NDVI trend, black spruce did not exhibit a short-term postdrought response (Fig. 6). Yet other studies have found a clear black spruce drought response in the tree-ring record (Wilmking and Myers-Smith 2008; Beck et al. 2011). The short-term response is consistent with an eddy covariance study (Welp et al. 2007) during the 2004 drought in boreal Alaska in which gross primary production decline was smaller in a black spruce stand compared with an aspen stand. This may be due to higher soil moisture (Kljun et al. 2006) and less evapotranspiration in black spruce stands (Welp et al. 2007; Zha et al. 2010). Balsam poplar NDVI departure below the trend line was not as strong as aspen, birch, or white spruce (Fig. 6). This may be due to the position of balsam poplar stands on lower elevation terraces of the Tanana River floodplain, where river levels rise in July during when glaciers in the Alaska Range melt at higher rates. Nossov et al. (2010) found alder growth less susceptible to drought stress on lower terraces where soil moisture replenishment during hot summers from the rising Tanana River is more likely.

This study provides further evidence of a changing boreal landscape in a region of interior Alaska that has warmed since the mid-1970s (Barber et al. 2004; Hartman and Wendler 2005). We found a consistent negative 1986–2009 trend in mean NDVI over time throughout the study area, regardless of landscape position or forest type. This trend is in contrast to increasing mean NDVI with revegetation after fire disturbance and no significant trend in wetland classes. A

Table 5. Correlation matrix (Pearson's R) 1986–2009 mean NDVI value by vegetation class within the study area (excluding burned pixels) (n = 11 years).

	Floodplain white spruce	Balsam poplar	Floodplain mixed forest	Upland white spruce	Non-acidic black spruce	Quaking aspen	Alaska birch	Upland mixed forest	Acidic black spruce
Floodplain white spruce	1.0	0.78	0.96	0.89	0.74	0.64	0.93	0.96	0.70
Balsam poplar		1.0	0.91	0.58	0.92	0.50	0.82	0.86	0.89
Floodplain mixed forest			1.0	0.79	0.84	0.63	0.94	0.96	0.81
Upland white spruce				1.0	0.65	0.49	0.76	0.88	0.64
Non-acidic black spruce					1.0	0.40	0.79	0.87	0.98
Quaking aspen						1.0	0.69	0.61	0.27
Alaska birch							1.0	0.95	0.74
Upland mixed forest								1.0	0.83

Note: See Table 2 for full species names.

Fig. 6. The 2006 NDVI departure from the 1986–2009 trend line (standardized residuals) by vegetation class.

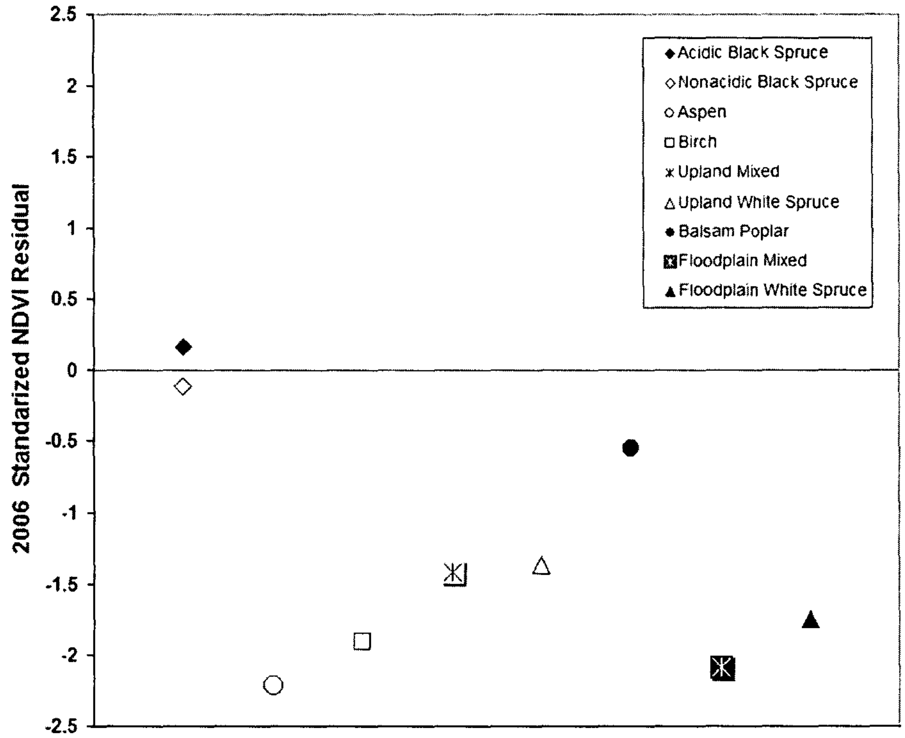


Fig. 7. June versus August mean NDVI within the wetland polygon likely influenced by surface water and herbaceous plant phenology.

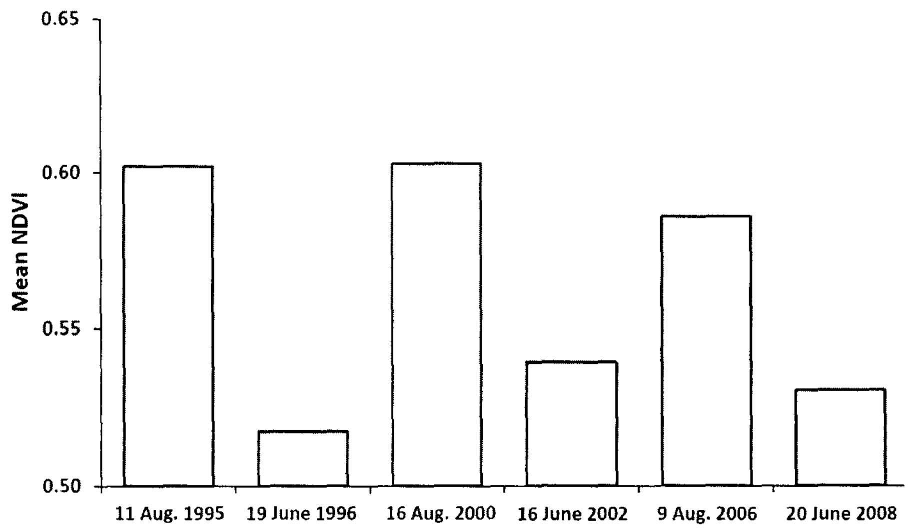
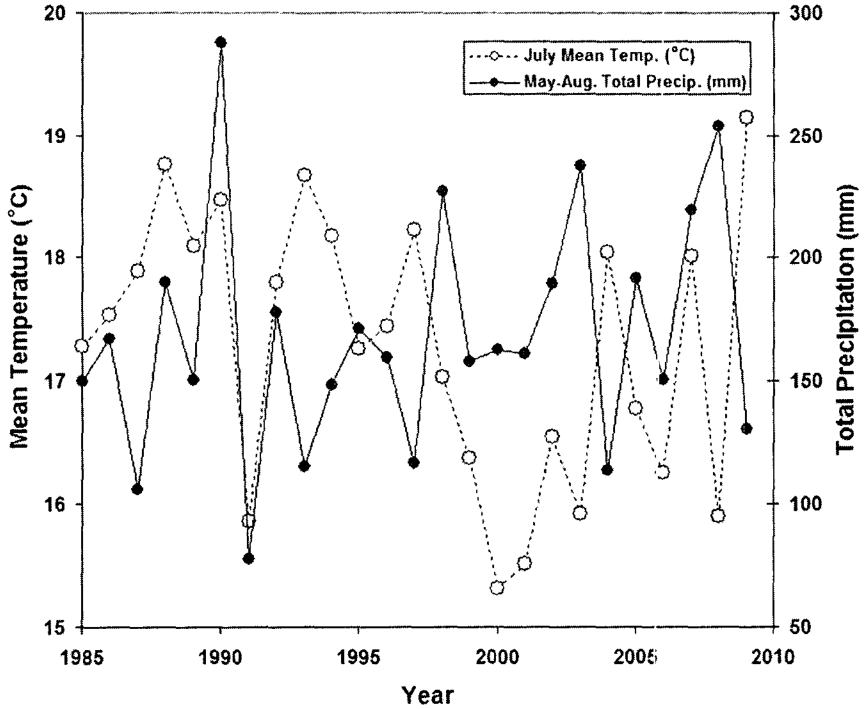


Fig. 8. The 1985–2009 July mean temperature (°C) and total May–August precipitation (mm) from nearby Fairbanks International Airport (source: http://climate.gi.alaska.edu).



time series of NDVI from Landsat sensors can complement coarser-resolution regional NDVI from other sensors. For example, Beck and Goetz (2011) found that from a regional perspective, based on 64 km^2 pixels, declining spruce NDVI appeared to be more frequent relative to declining deciduous NDVI. However, this pattern may be due to regional climatic gradients. At our smaller landscape scale, both deciduous and white spruce vegetation types had similar browning trends, sometimes with adjacent white spruce and birch stands having nearly identical declining NDVI trends.

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