Impact of burn severity on thermokarst initiation and expansion in Arctic tundra ecosystems

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Abstract

Burn severity influences various biophysical and biogeochemical processes, and it is projected to increase in the coming decades across high-latitude ecosystems. However, the impact of burn severity on thermokarst (e.g., land subsidence after ground ice melting) is not well understood. We used time-series image analysis to assess the effects of burn severity and ground ice content on thermokarst processes in the Noatak National Preserve, northwestern Alaska. To extend the temporal depth for illustrating fire-thermokarst linkages, we evaluated eight existing fire indices derived from visible and near-infrared (380-1100 nm) spectral bands and developed burn severity maps of historical fires using Landsat MSS sensors (operation between 1972-1992). Our results reveal that tundra fire is a significant factor in creating thermokarst landforms ($p<0.01$), and that the magnitude of thermokarst varies with burn severity levels and ground ice content ($p<0.05$). An abrupt increase in thermokarst occurred one year after fire but the rate of thermokarst decreased after three years. The area of thermokarst three years after fire was highest in high-severity burns (385 ± 47 m2 thermokarst area/ha burned area), followed by moderate- (255 ± 32 m2/ha) and low-severity (201 ± 42 m2/ha) burns. Ground ice content interacted with burn severity to affect thermokarst; the area of thermokarst was twice as large in landscapes with high ground ice (356 ± 67 m2/ha) as in landscapes of low ground ice (167 ± 39 m2/ha) three years after fire. Among the eight fire indices, the Global Environmental Monitoring Index (GEMI) demonstrates the strongest correlation with field-based estimates (R2 = 0.8). Burn-severity maps reconstructed with GEMI reveal that over a 40-year study period, thermokarst expansion occurred more rapidly in high-severe burns than in low-severity or unburned areas. Our results suggest that the projected increase in burn severity may result in abrupt and long-lasting permafrost degradation in tundra ecosystems with potential consequences on Arctic carbon stocks.

A robust visible-near-infrared burn severity index for tundra ecosystems

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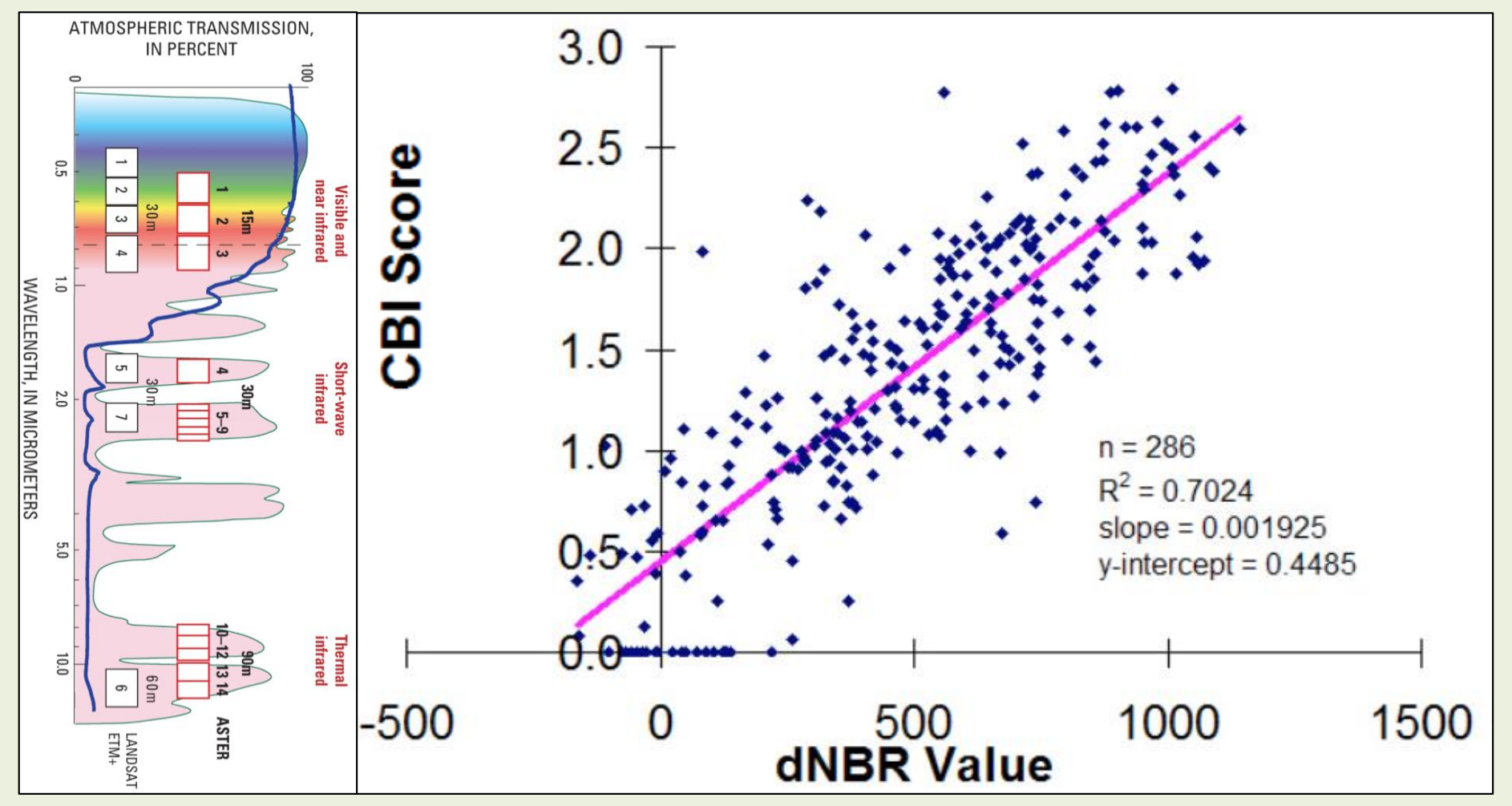
Introduction

Wildfire is an ecologically important process that impacts terrestrial, aquatic, and atmospheric systems. Burn severity is of particular interest to scientists and resource managers because of its control on various above- and below-ground processes, yet our ability to evaluate burn severity is still limited.

Normalized Burn Ratio (NBR) is commonly applied for burn severity assessment using Landsat sensors. However, the relatively coarse spatial-resolution of Landsat imagery and the lack of short-wave infrared data in most optical imaging platforms constrain NBR from capturing the burn severity patterns in heterogeneous landscapes.



Rationale and Methods

Search for a visible-near-infrared burn index to leverage historical and high-resolution imagery for improved understanding of tundra fire ecology.

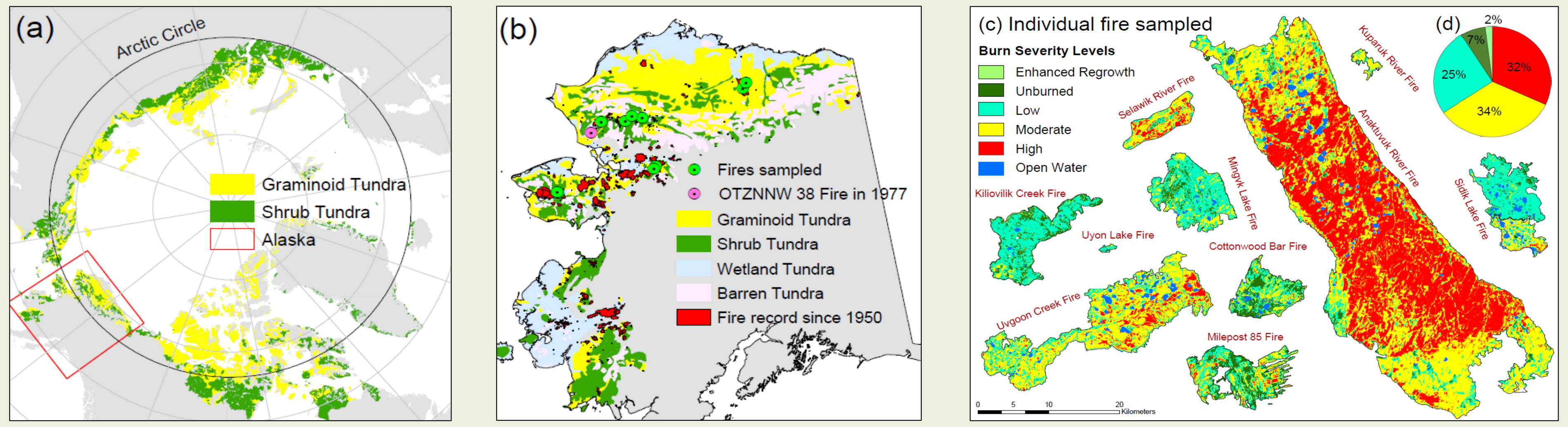


Fig. 1. Study sites. (a) Circumpolar Arctic tundra biome. (b) Observational fire records in Alaska tundra (AICC, 1950 - 2018). (c) dNBR burn severity maps of sampled fires. (d) Percentages of area burned by severity levels.

Indices	Formula	Reference
NBR	$\frac{NIR-SWIR}{NIR+SWIR}$	Garcia & Caselles, 1991
NDVI	$\frac{NIR-R}{NIR+R}$	Tucker, 1979
GNDVI	$\frac{NIR-G}{NIR+G}$	Gitelson & Merzlyak, 1998
SAVI	$(1+L)*\frac{NIR-R}{NIR+R+L}, where\ L = 0.5$	Huete, 1988
MSAVI	$\frac{1}{2}*\left(2*NIR+1-\sqrt{(2*NIR+1)^2-8*(NIR-R)}\right)$	Qi et al., 1994
GEMI	$\gamma*(1-0.25*\gamma)-\frac{R-0.125}{1-R}$, where γ is $\frac{2*(NIR^2-R^2)+1.5*NIR+0.5*R}{NIR+R+0.5}$	Pinty & Verstraete, 1992
BAI	$\frac{1}{(0.1-R)^2+(0.06-NIR)^2}$	Chuvieco et al., 2002
NIR	NIR	Hall et al., 1980

Table 1. NBR and VNIR Burn Indices. NDVI: Normalized Difference Vegetation Index; GNDVI: Green NDVI; SAVI: Soil-Adjusted Vegetation Index; MSAVI: Modified SAVI; GEMI: Global Environmental Monitoring Index; BAI: Burn Area Index; G: Green spectral band; R: Red spectral band; NIR: Near-Infrared

Results

Table 2. Coefficients of determination (R^2) between remotely sensed burn indices and field-based CBI (n = 102, pooled from all five fires).

Bi-temporal Index	R^2	Rank	Uni-temporal Index	R^2	Rank	Score
dGEMI	0.82	1	GEMI	0.77	1	2.00
dNBR	0.81	2	NBR	0.77	1	1.50
dMSAVI	0.74	3	MSAVI	0.63	4	0.58
dSAVI	0.69	4	SAVI	0.69	3	0.58
dNIR	0.62	5	NIR	0.57	5	0.40
dGNDVI	0.49	6	GNDVI	0.44	6	0.33
dNDVI	0.43	7	NDVI	0.39	8	0.27
dBAI	0.31	9	BAI	0.29	9	0.22

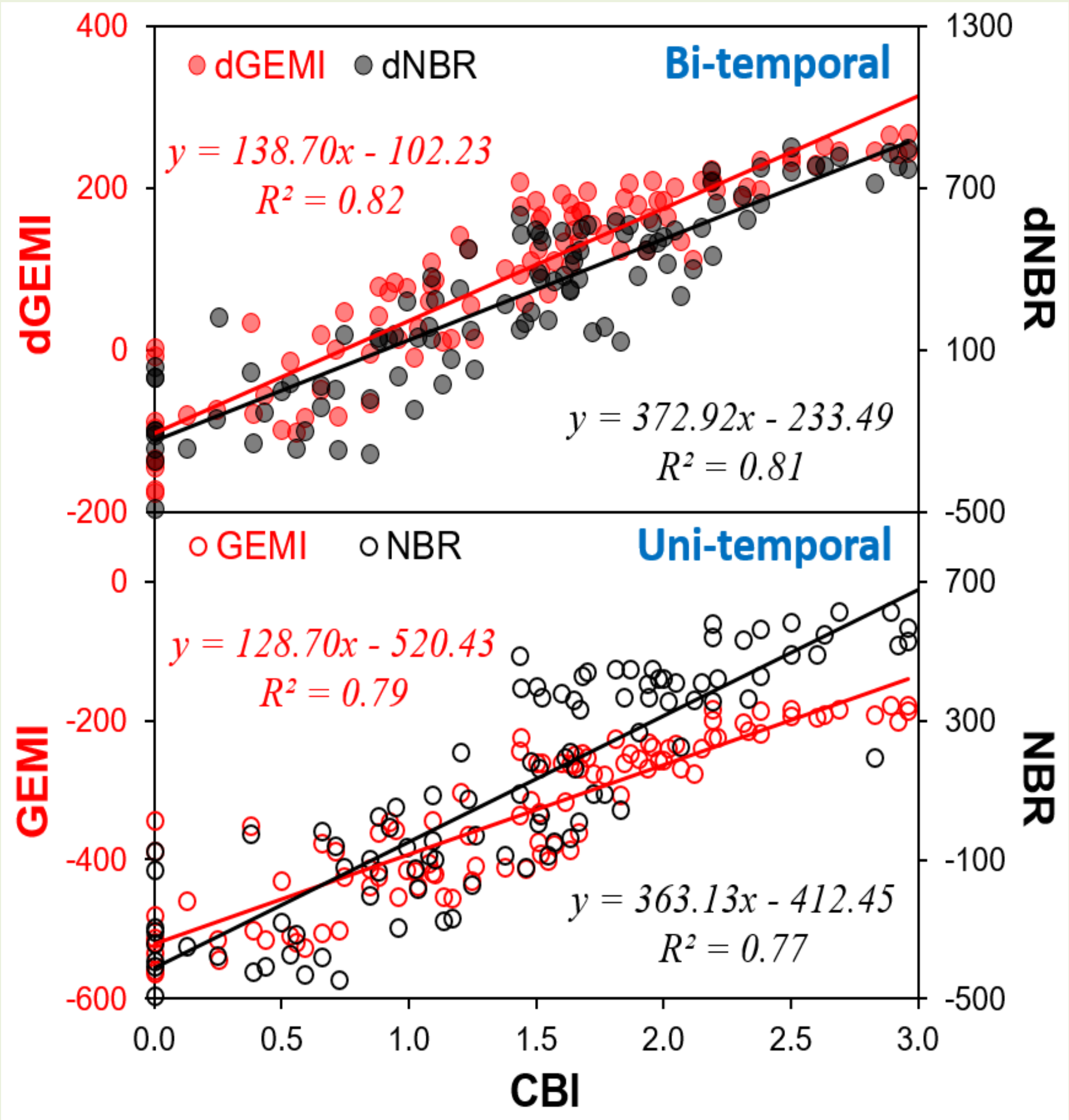


Fig. 2. Validation of NBR and GEMI with CBI (n = 102). The solid lines and functions are based on linear regression analysis.

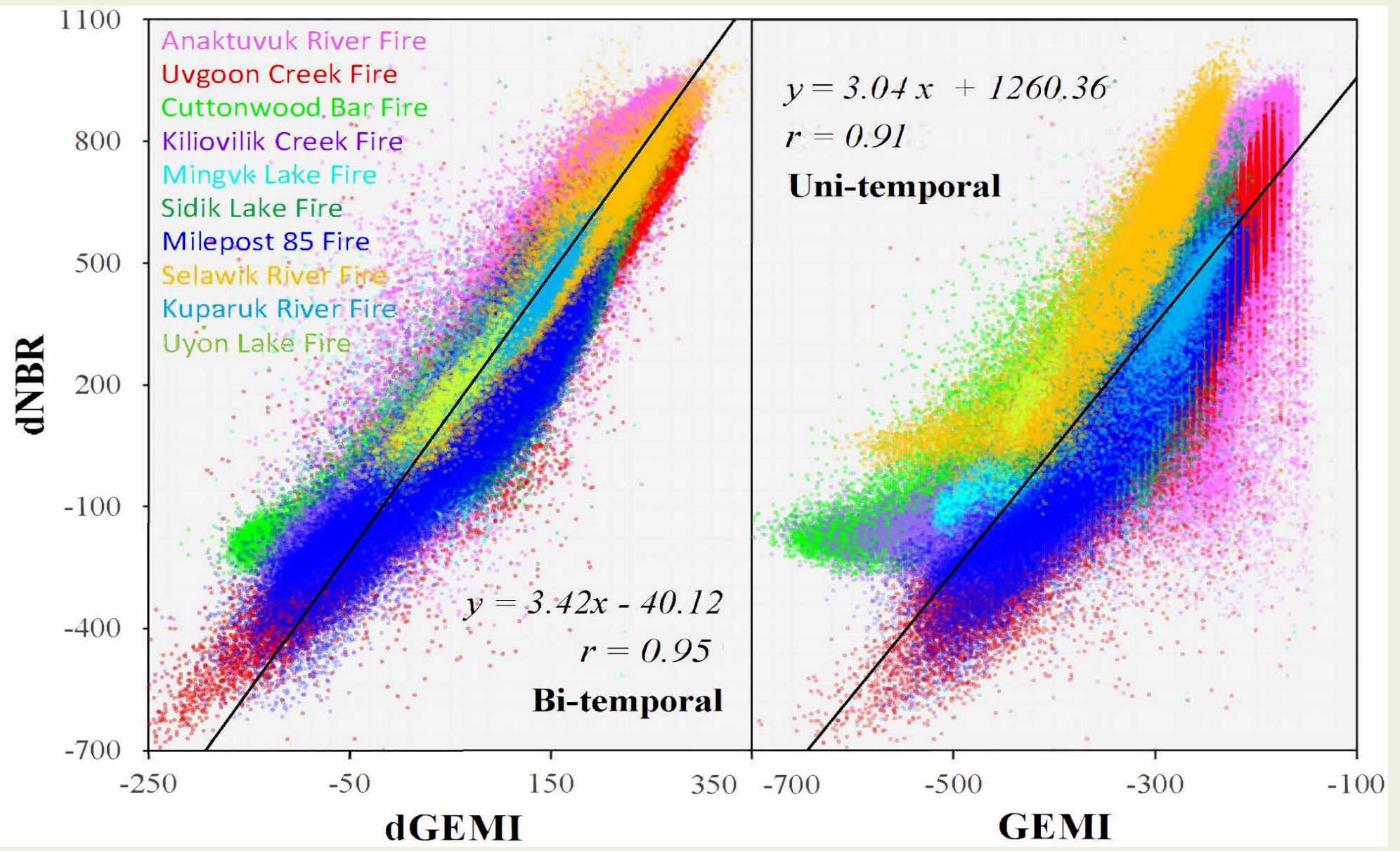


Fig. 3. Correlation analysis between dNBR and dGEMI (left), and between dNBR and GEMI (right).

Application with high-resolution multispectral imagery

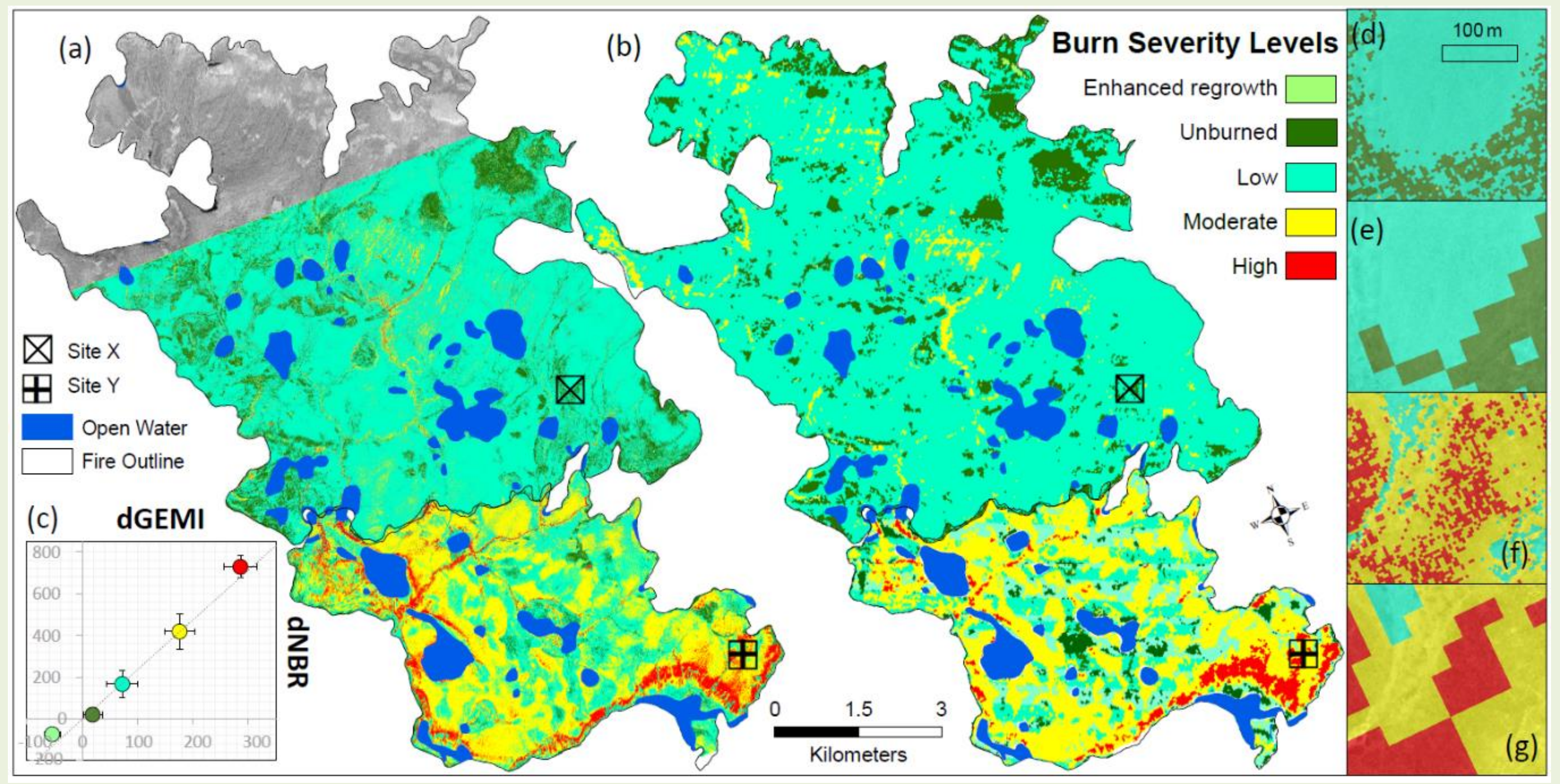


Fig. 4. Application of dGEMI using multispectral high-resolution image. (a) dGEMI burn severity map (4 m). (b) dNBR burn severity map (30 m). (c) Correlation between dGEMI and dNBR Panel (d) and (e) are the dGEMI map and the dNBR map zoomed to Site X, and (f) and (g) are the same maps zoomed to Site Y.

Application to historical fire

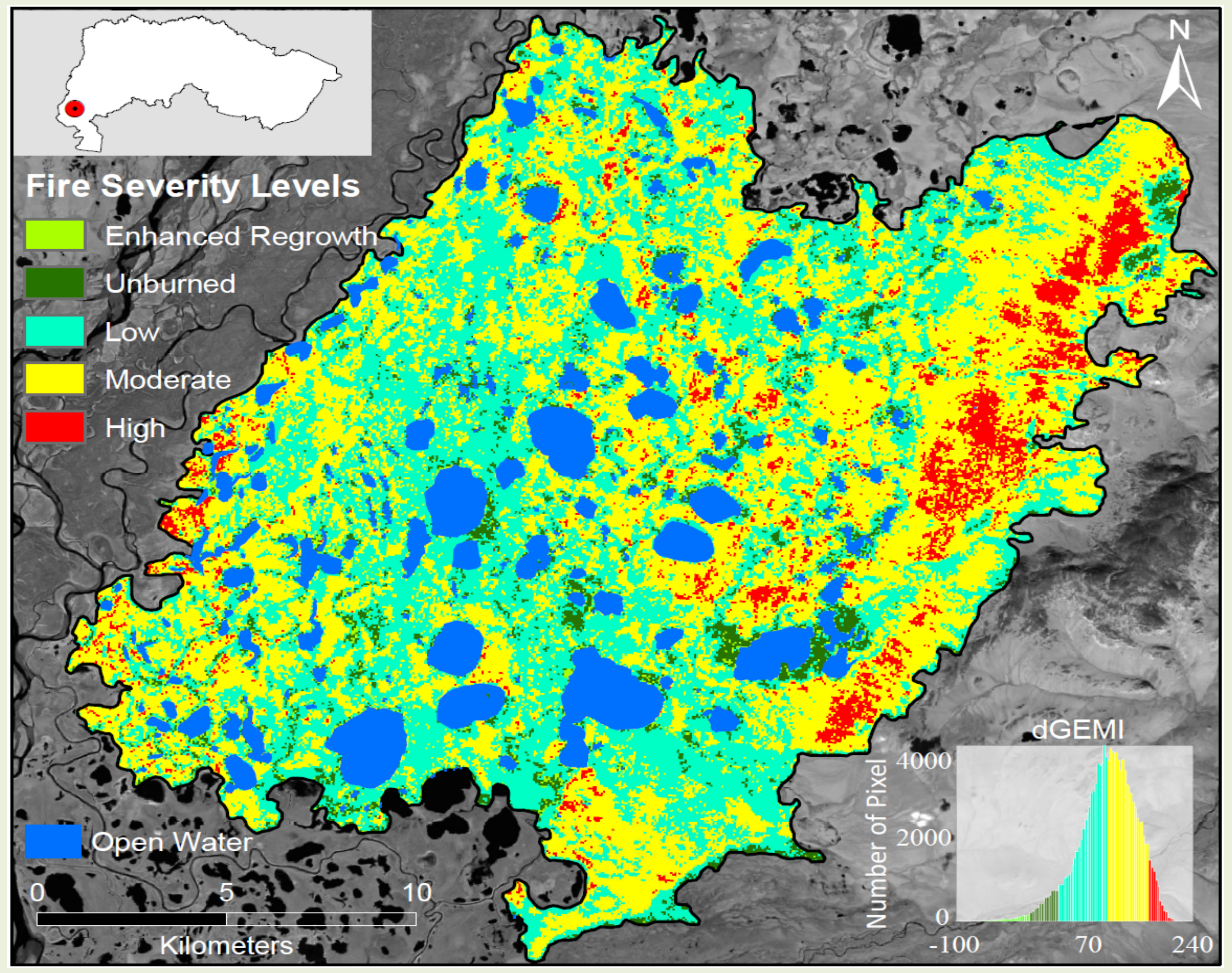


Fig5. Burn severity map of the OTZNNW 38 Fire in 1977 using dGEMI. The panel on top left indicates the location of this fire (red dot) in the Noatak River Watershed and the panel on bottom right shows the frequency histogram of dGEMI values.

Conclusion

- ➢ The Global Environmental Monitoring Index (GEMI) is a robust alternative to NBR, opening new opportunities for wildfire assessment in tundra ecosystems.
- ➢ High-resolution application with GEMI enables detailed depiction of burn severity pattern in heterogeneous landscape.
- ➢ The GEMI can be used to retrieve burn severity information for historical disturbance events that help unravel long-term interactions between fire and other ecological processes in tundra ecosystems.

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