ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

20 years of change in tundra NDVI from coupled field and satellite observations

To cite this article: K Fred Huemmrich *et al* 2023 *Environ. Res. Lett.* **18** 094022

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
2 June 2023

REVISED
20 July 2023

ACCEPTED FOR PUBLICATION
8 August 2023

PUBLISHED
17 August 2023

LETTER

20 years of change in tundra NDVI from coupled field and satellite observations

K Fred Huemmrich[1,*], John Gamon[2], Petya Campbell[3], Marianna Mora[4], Sergio Vargas Z[5], Brenda Almanza[6] and Craig Tweedie[7]

[1] University of Maryland Baltimore County, 5523 Research Park Drive Suite #140, Baltimore, MD 21228, United States of America
[2] School of Natural Resources, 307 South Hardin Hall, 3310 Holdrege St., Lincoln, NE 68583–0988, United States of America
[3] UMBC, 5523 Research Park Drive Suite #140, Baltimore, MD 21228, United States of America
[4] UTEP, Biological Sciences Building, Room B-413, El Paso, TX 79968, United States of America
[5] UTEP, Biological Sciences Building, Room 418, El Paso, TX 79968, United States of America
[6] UTEP, El Paso, TX 79968, United States of America
[7] UTEP, 104 Kelly Hall, El Paso, TX 79968, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: huemmric@umbc.edu

Keywords: change, tundra, NDVI, satellites, observations

Abstract

In 2022 we resampled normalized difference vegetation index (NDVI) along a 100 m transect in tundra near Utqiagvik, AK that had been previously measured through the 2000–2002 growing seasons, providing an opportunity to examine a 20 year NDVI change at a 1 m resolution in a region that is experiencing increased warming and precipitation over this period. Multidecadal NDVI change was spatially variable across the transect with nearly half of the transect showing greening, about a third not showing conclusive change, and about 20% browning. In wet areas, greening (increased NDVI) was associated with increased green leaf area index, while in drier areas greening was related to changes in species cover. Browning was not related to change in species cover and appeared to be due to increased coverage of standing dead material in graminoid dominated canopies. These types of detailed observations provide insights into the interpretation of satellite based NDVI trends and emphasize the importance of microtopography and hydrology in mediating vegetation change in a warming Arctic.

1. Introduction

Numerous studies have used satellite observations to describe high latitude vegetation change over decadal and longer time periods at moderate spatial resolutions using the normalized difference vegetation index (NDVI) (for example, Myneni *et al* 1997, Goetz *et al* 2005, Jia *et al* 2009, Bhatt *et al* 2013, 2017, Guay *et al* 2014, Ju and Masek 2016, Huang *et al* 2017, Zhang *et al* 2017, Wang and Friedl 2019, Jenkins *et al* 2020, Frost *et al* 2022). These high latitude ecosystems are experiencing rapid climate change, and these satellite studies have shown a range of responses by NDVI with increasing trends (greening) in some areas, decreasing trends (browning) in others, and yet other areas showing no significant change (Myers-Smith *et al* 2020). NDVI has been related to key tundra vegetation characteristics such as plant cover, green leaf area index (LAI), aboveground biomass, and vegetation productivity, providing a link between the satellite observations and ecological conditions (for example, Walker *et al* 2003, Riedel *et al* 2005, Steltzer and Welker 2006, Huemmrich *et al* 2010a, 2010b, Epstein *et al* 2012, Raynolds *et al* 2012, Pattison *et al* 2015). NDVI can also be affected by hydrology and snowcover, both through direct optical effects and indirect effects mediated by vegetation change (Huemmrich *et al* 2010a, Gamon *et al* 2013). The satellite data, however, are sampled at spatial scales that make it difficult to describe the actual ecological changes that are occurring on the ground. There are very few studies that provide ground measured NDVI at specific locations along with associated observations of tundra change that extend beyond a few years, leading to many authors to infer biological change without direct observation of surface conditions. Long term collections of land cover descriptions are valuable in that they can link observed tundra change with NDVI signals over time scales similar to the satellite record (Harris *et al* 2021, Callaghan *et al* 2022).

In August of 2022 we were able to remeasure a 100 m transect in an area of tundra near Utqiagvik, AK that was established by Gamon *et al* (2013) in 2000 and previously measured through the 2000–2002 growing seasons, providing us with the opportunity to examine a 20 year NDVI change in a meter scale in comparison to the year-to-year change observed in the early 2000s. The transect was located in an area representative of the footprint of the San Diego State University Barrow flux tower (US-BRW, Kwon *et al* 2005) and there are clear indications of tundra change in the area around Utqiagvik in the satellite record with this region showing a strong greening (positive) trend over the 22 year moderate resolution imaging spectroradiometer (MODIS) NDVI record, as well as the summer maximum MODIS NDVI in 2022 being greater than the average summer maximum NDVI over the MODIS record (Frost *et al* 2022). Further, multiyear greening trends in Landsat NDVI from 1999 to 2014 were found, however over the North Slope of Alaska increases in NDVI with air temperature were limited in areas of high centered polygons such as around the transect (Lara *et al* 2018).

Plot level manipulation studies made near Utqiagvik found that even short-term warming through either soil heaters or open top chambers yielded increased leaf area index, canopy height, and relative cover resulting in increased NDVI (Hollister *et al* 2005, Huemmrich *et al* 2010b). Further, studies of tundra vegetation plots in this area over decadal periods found increased graminoid cover and height with decreased lichen cover (Hollister *et al* 2015, Harris *et al* 2021).

Our repeat NDVI measurements along this transect provide the opportunity to observe and quantify over 20 years of NDVI change at high spatial resolution (1 m) and to infer the specific causes of this change. Such field validation is critical to the proper interpretation of changes seen in the satellite record over longer time scales and larger spatial scales.

2. Methods

2.1. Site description

Field optical measurements were collected along a 100 m transect (endpoint latitude–longitude coordinates: 71.321974° N, −156.604369° E and 71.322071° N, −156.601561° E) located approximately 300 m southeast of the National Oceanic and Atmospheric Administration (NOAA) Global Monitoring Laboratory baseline observatory near Utqiagvik, AK (BRW) (Gamon *et al* 2013, figure 1).

The transect crosses a landscape of wet sedge wetland tundra patterned ground with high centered polygons producing microtopographic variations between troughs and the higher polygon centers. (Brown *et al* 1980). In a land cover map based on WorldView satellite imagery with 18 land cover classes based on the National Wetlands Inventory classification, the area along the transect was identified as a combination of palustrine emergent persistently saturated and emergent persistent temporarily flooded wetlands (Andresen *et al* 2016). Over a local region of 293 km^2 these landcovers represent 40% of the area.

Common vascular species in this area include: *Carex aquatilis, Dupontia fischerii, Eriophorum angustifolium, Eriophorum scheuzerii, Luzula confusa, Petasites frigidus, Potentilla hyparctica,* and *Salix rotundifolia*. Mosses are also a significant part of this community and common species include: *Dicranum elongatum, Dicranum undulatum, Drepanocladus revolvens, Polytrichum juniperinum*, and *Sphagnum* spp. Lichens occur in drier areas and include the species: *Alectoria nigricans, Cetraria cucullata, Cetraria nivalis*, and *Dactylina arctica* (Gamon *et al* 2013).

2.2. Ground measurements

Ground spectral reflectance measurements were collected at 1 m intervals along the 100 m transect using a dual channel spectroradiometer (Unispec DC, PP Systems). This spectrometer has two fiber-optic cables, one with a diffuser head viewing upward and the other pointing vertically downward to view the ground. Each measurement simultaneously collects both reflected radiance and incident irradiance that are used to calculate surface reflectance. The instantaneous coincident measurements of both incoming and reflected radiation can correct for variability in illumination conditions when calculating surface reflectance (Gamon *et al* 2013). Measurements viewed the area to the south of the transect with a nadir view. In 2000 and 2001 a track supported by tripods was constructed along the transect with the track positioned less than a meter above the ground (figure 1). In these years reflectance data were collected using a tram cart that carried the spectrometer along the track and suspended the fiber optics in a vertical (nadir) position over the landscape. The track was marked at meter intervals for accurate spatial location of repeat measurements. The tram tracks were not installed for the 2002 and 2022 measurements. For these measurements a 100 m tape measure was extended along the transect to locate points and the spectrometer measurements were collected by a person carrying the spectrometer (Gamon *et al* 2013). In 2022 the end points of the transect were located based on GPS measurements collected in 2002. The exact recorded locations were verified in 2022 by a

Figure 1. Two photos of the eastern end of the transect looking west. Left photo taken 30 July 2001 and shows the track used to carry the tram with the spectrometer on it. Right photo taken 7 August 2022. The NOAA GRL buildings can be seen in the background.

stake marking the western end of the transect that remained in place since 2002.

In processing the spectrometer data to surface reflectance the reflectance data were averaged to 5 nm spectral bands. NDVI was calculated from the reflectances as:

$$\mathrm{NDVI} = (\mathrm{R800} - \mathrm{R670}) / (\mathrm{R800} + \mathrm{R670}) \quad (1)$$

where R800 is the reflectance at 800 nm and R670 is the reflectance at 670 nm.

During the 2000–2002 field seasons, transect reflectance spectra were collected at approximately weekly intervals. To focus on multiyear change in this study we use the summer maximum NDVI for each year, selecting measurements collected on 4 August 2000, 4 August 2001 and 10 August 2002, which represent the seasonal maximum transect average NDVI from the weekly observations in those years, to compare with the single 2022 measurement collected on 7 August 2022. All measurements were collected near midday under full cloudy conditions. To highlight temporal change along the transect, an NDVI anomaly was calculated by subtracting the average NDVI from years 2000–2002 for each meter from the observed NDVI for that meter.

Digital photos were taken at every meter along the transect on 11 August 2001 and once again on 7 August 2022. These photos provide a visual record to compare changes in vegetation cover. In addition, a more quantitative visual estimate of species cover was made over the period 8–11 August 2001 using a 1 m by 1 m quadrat (Gamon *et al* 2013, Huemmrich *et al* 2013).

As described in Gamon *et al* (2013) the measured elevation changes along the entire length of the transect are only about 1 m in total, but minor elevation differences have a significant effect on localized moisture and temperature condition. Local depressions with depths of 10–40 cm can accumulate water and are typically wetter. They also accumulate snow in the winter and the deeper snowpack helps to protect the plants from temperature extremes and wind damage compared to the higher polygon centers (Abolt *et al* 2018). In the lower areas this results in deeper summertime active layer depths (Gamon *et al* 2013, Hubbard *et al* 2013). This microtopographic variation produces persistent localized moisture and temperature patterns that influence species distribution and productivity along the transect, and thus NDVI (Gamon *et al* 2012, 2013). For example, the 2001 vegetation survey found the locally low areas had the highest vascular plant cover, mainly graminoids, in places with standing water. Moss coverage was also high in the lower areas without standing water or adjacent to wet areas, while the relatively drier locally high areas had the highest lichen coverage (Huemmrich *et al* 2013). In the measurements through the 2000–2002 growing seasons the locally lower wetter areas tended to have the highest NDVI seasonal change resulting in higher mid-summer NDVIs than the higher elevation drier areas (Gamon *et al* 2013).

2.3. Satellite observations

To place the transect measurements in the context of multiyear satellite observations, a time series of MODIS NDVI values from the MOD13 product were extracted for the 250 m pixel containing the transect using the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) MODIS subsetting tool (ORNL DAAC 2018, Didan 2021). Out of this time series, the maximum summer NDVI were determined for each year of the MODIS record.

2.4. Weather observations

Daily weather observations of maximum and minimum air temperature and precipitation from 1999 through 2022 were acquired from the NOAA National Centers of Environmental Information (www.ncei.noaa.gov/cdo-web/) for the Barrow Airport (Station

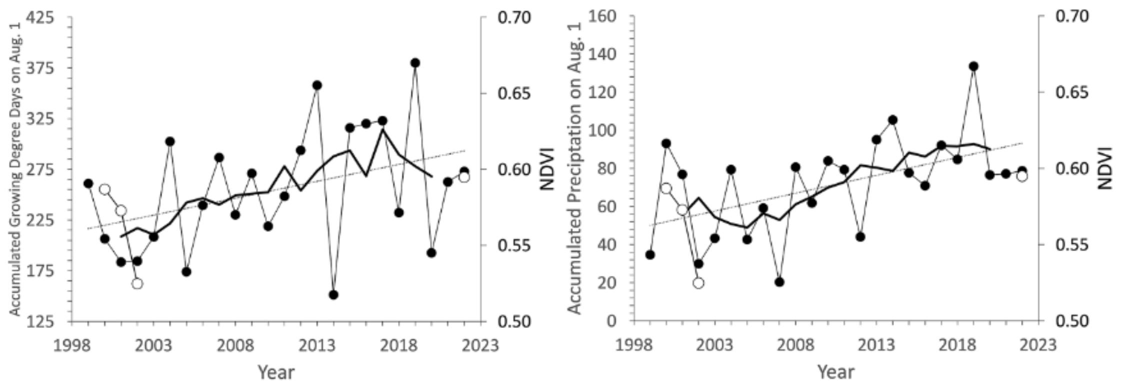

Figure 2. Filled black points are the accumulated GDD (left plot) and precipitation (right plot) from start of year to 1 August measured at the Barrow Airport approximately 7 km from transect. The heavy black line is the 5 year running average of the accumulated values and the dotted line is a linear regression of the values. Unfilled points are the transect average midsummer maximum NDVI.

USW00027502). The airport weather station is located approximately 7 km from transect site. To summarize environmental conditions related to warmth and water availability, accumulated values of growing degree days (GDDs) and precipitation up to 1 August of each year were determined from the daily weather data. Accumulated GDD were calculated as the difference between the average of the daily minimum and maximum air temperature and 0 °C, summing up positive values from day to day. Accumulated precipitation was the sum of daily precipitation in mm.

3. Results

3.1. Environmental change

Temperature and moisture are key variables determining productivity and carbon balance of arctic tundra (Huemmrich *et al* 2010a, 2010b). We have used accumulated GDD and accumulated precipitation to characterize the midsummer local climate conditions. While there are strong year to year variations in both GDD and precipitation, there are general trends toward warmer and wetter conditions over the period from 2000 to 2022 as illustrated by the linear regression lines as well as in the trends of the 5 year running averages (figure 2). The linear regressions show an increasing trend of 3.3 °C day per year for GDD which represents a 32% increase over the period from 2000 to 2022, along with an increase of 1.9 mm per year of accumulated precipitation or a 49% increase from 2000 to 2022.

In the years with ground measurements, 2022 was warmer than any of the years in the 2000–2002 period based on accumulated GDD. The three years of 2000–2002 were a drying period where the accumulated precipitation dropped from one of the wetter years in 2000 to one of the drier in 2002. While there is a general trend toward wetter conditions over the 2000–2022 period, 2022 falls near the middle of the range of accumulated precipitation for 2000–2002 period.

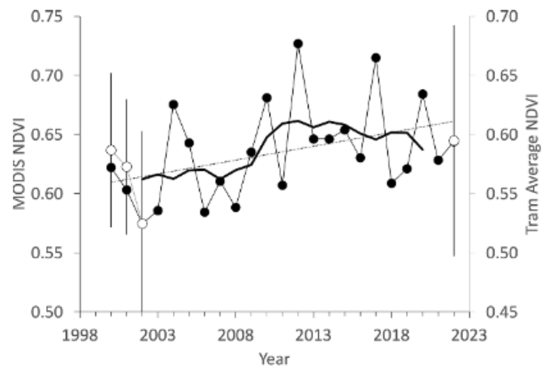

Figure 3. Temporal change in summer maximum NDVI. Black points are the summer maximum MODIS NDVI for the 250 m pixel that includes the transect. The heavy black line is the 5 year running average of the MODIS NDVI values and the dotted line is a linear regression of those values. Unfilled points are the average of the transect midsummer maximum NDVIs and their error bars are ±1 standard deviation of the transect NDVI values. Note the offset of 0.05 NDVI units in the y-axis scales for the MODIS and tram average NDVIs.

3.2. MODIS NDVI

The MODIS NDVI is similar to the tram average NDVI, but with a slight offset (figure 3). This offset is most likely due to differences in area observed between the narrow transect and the entire MODIS 250 m pixel but can also be affected by the slightly different NDVI formulas used and by the effects of atmospheric correction (Gamon *et al* 2013, Assmann *et al* 2020).

Like the GDD and precipitation, the summer maximum MODIS NDVI over the period from 2000 to 2022 shows strong year to year variability with the greatest change from one year to another of over 0.1 NDVI units, as well as an overall increasing trend of 0.0023 NDVI units per year based on a linear regression (figure 3). However, the 5 year running average suggests the increase in NDVI occurred mainly between 2007 and 2012, and since 2012 there has been a slight decrease in the 5 year average NDVI trend.

Table 1. Average, standard deviation, maximum, and minimum NDVI values across the 100 m transect ($n = 100$) (figure 1) for observations near maximum summer greenness.

Year	Average	Standard deviation	Maximum	Minimum
2000	0.587	0.065	0.752	0.470
2001	0.573	0.057	0.716	0.468
2002	0.525	0.078	0.713	0.396
2022	0.595	0.098	0.839	0.407

Over 2000–2002 period both MODIS and average transect NDVI appear to track the change in precipitation (Gamon *et al* 2013). However, over all the years there were poor correlations between MODIS NDVI and the accumulated precipitation ($r = 0.19$) or GDD ($r = 0.30$). The temperature response varies over the study period as the correlation of NDVI with GDD is much greater over the period before the 5 year NDVI running average trend flattens from 2000 to 2012 ($r = 0.50$) compared to the later part of the time series from 2011 to 2022 ($r = 0.04$) (Bayle *et al* 2022).

3.2.1. Spatial variability in ground measurements

Along the transect, NDVI can vary widely resulting in standard deviations of transect NDVIs being as large as year-to-year differences in the MODIS NDVI (figure 3, table 1). Further, significant variability in NDVI occurs over short distances. For example, NDVI changes of over 0.2 units occur within just a few meters (figure 4, Gamon *et al* 2013) as has been observed in other locations (Assmann *et al* 2020). This spatial variation in NDVI is associated with the local microtopography, with low areas generally leading to higher peak season NDVI values. These microtopographic patterns persisted and in several locations appear to become enhanced over the ∼20 years sampling period.

3.2.2. Multiyear ground measurements

NDVI anomalies, the difference between the average NDVI from years 2000–2002 and the observed NDVI for each meter, were used to highlight temporal change and minimize spatial variability across the transect. Since there can be significant year-to-year variability in NDVI and we wish to identify areas changing beyond that short term change, we calculated the maximum and minimum NDVI anomalies over the 2000–2002 period for each meter to describe year-to-year variability and consider 2022 values outside of that range to be indicative of multi-decadal changes. In figure 5 the gray lines indicate the range of possible short term NDVI change (i.e. change over the 3 year period 2000–2002) compared to the longer term change by 2022, shown by the green line. In 2022, not all points along the transect showed changes outside of the year-to-year range. Of the 100 locations along the transect 47 had an NDVI in 2022 greater

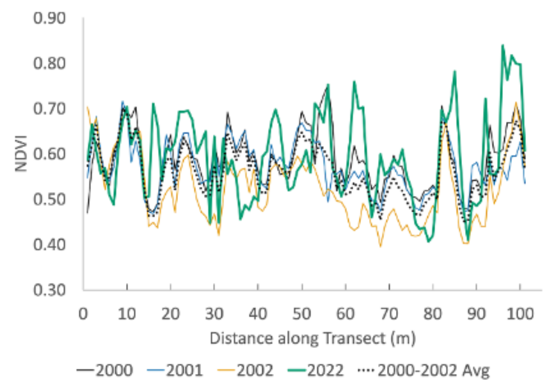

Figure 4. NDVI values for every meter along the 100 m transect for seasonal maximum NDVI. Dotted line is the average of 2000–2002 values used for calculating NDVI anomaly (figure 5).

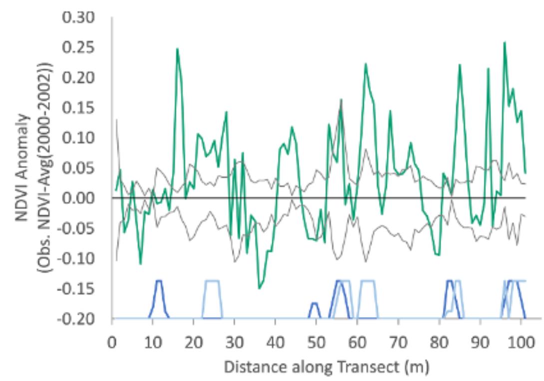

Figure 5. NDVI anomaly (NDVI minus the average NDVI for maximum NDVI for years 2000–2002) along transect (heavy green line). Thin gray lines show the NDVI anomaly for the maximum and minimum midsummer NDVI over the 2000–2002 period. Blue lines at bottom of the plot indicate the presence of surface water in 2001 (dark blue) and 2022 (light blue).

than the observed 3 year 2000–2002 maximum which we consider to be greening, 19 had an NDVI less than the observed 3 year 2000–2002 minimum and could be described as browning, and 34 had NDVI values within the variation in the 3 year values.

Photos taken at every meter along the transect in August 2001 and in 2022 were used to qualitatively describe vegetation change between those observations. The areas with large NDVI change were mainly located in the locally lower areas and were not moisture limited. These sites were in or near surface water and were dominated by *Eriophorum* (figures 6(c)–(f)). The higher and relatively drier areas with increased NDVI had increased *Petasites* or *Vaccinium* cover (figures 6(a) and (b)). 19% of the sites had significantly decreased NDVI in 2022, apparently due to increased fraction of standing dead leaves in the canopy (figures 6(g) and (h)). For 34% of the sites the 2022 NDVI were within the 2000–2002 variation and so were not considered to be displaying a long-term greening or browning response.

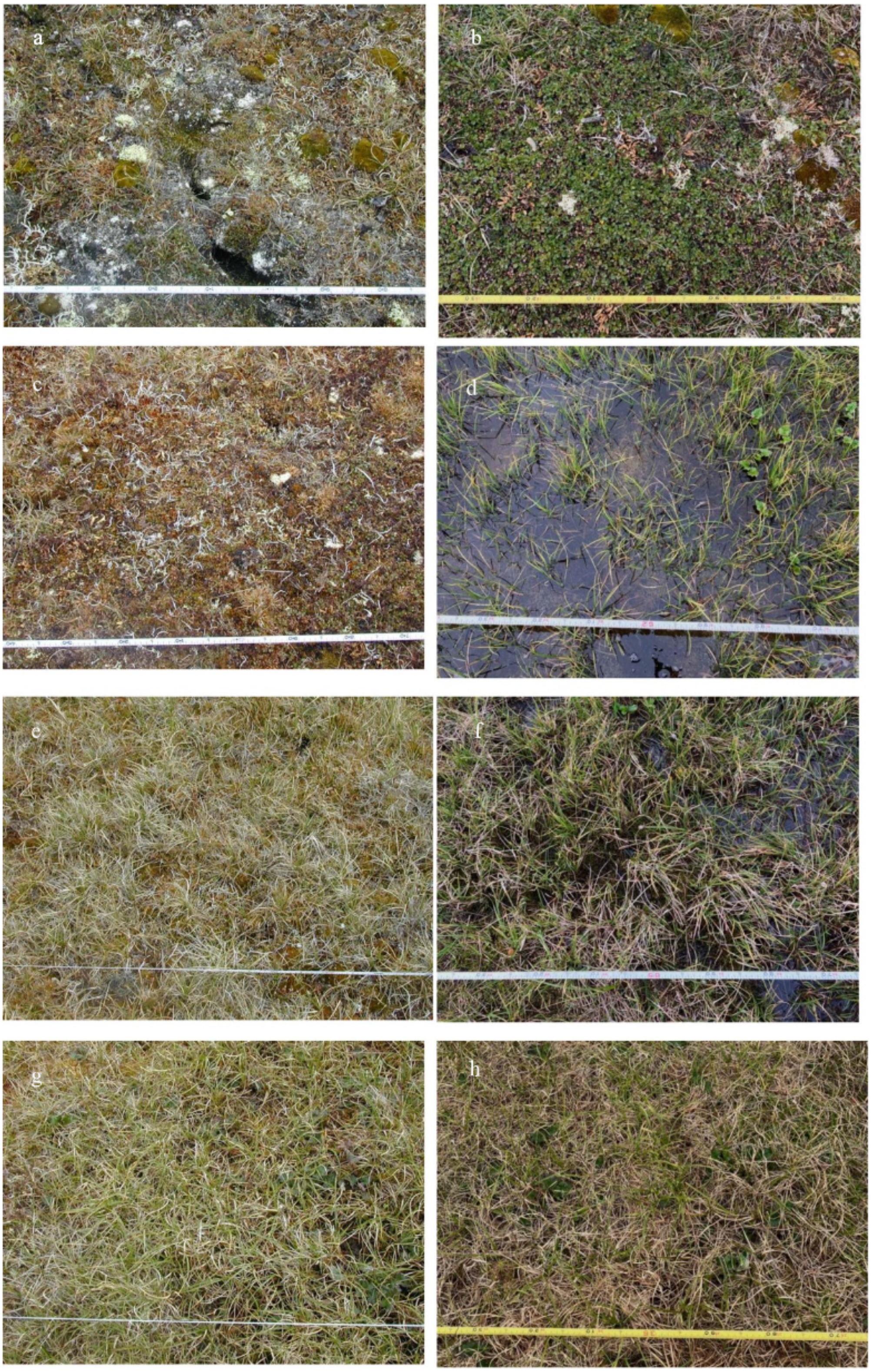

Figure 6. Photos of specific locations along the transect which are examples of significant NDVI change after 20 years (see figure 5). Left column photos were taken 11 August 2001 and right column photos were taken 7 August 2022. Photos (a) and (b) are at meter 16, (a) higher and drier location with increased NDVI. Photos (c) and (d) are at meter 62 and photos (e) and (f) are at meter 85, two examples of locally low wet areas with increased NDVI. Photos (g) and (h) are at meter 36, (a) location with decreased NDVI.

4. Discussion

Despite year-to-year variability over the 22 years we examined, the meteorology data clearly show that this area is experiencing trends of warmer and wetter conditions as seen in the accumulated GDD and precipitation records (figure 2). Over that same period, the summer maximum MODIS NDVI shows an increase (figure 3), but not significantly related to the accumulated GDD and precipitation climate variables. The transect ground measurements anchor the ends of the MODIS time series, as they are in general agreement, supporting the validity of the MODIS NDVI time series. Although the sampled area of the transect is a small fraction of a MODIS pixel, transect average NDVI track the MODIS values (see Gamon *et al* 2013 and figure 3).

Within an individual MODIS pixel there can be significant variability in tundra NDVI at the scale of a meter as shown by the values along the 100 m transect (figure 4). Microtopography and hydrology (surface moisture) define patterns of vegetation type and productivity, and thus can help reveal the nature of ecological responses to longer term climate change as evidenced in NDVI change. Multidecadal NDVI change was not consistent across the transect with nearly half of the transect showing greening, about a third not showing conclusive change, and about 20% browning, and this inconsistency was partly related to topographic variation.

Long-term greening occurred predominately in low, wet areas, most of which were the same areas that showed the greatest within-season greening in the original (2000–2002) study (Gamon *et al* 2013). Based on a visual evaluation of the 2001 and 2022 photos we infer that the increase in NDVI in these wetter areas was associated with an increase in green LAI with no change in species (figures 6(c)–(f)). In addition, modeling studies of tundra reflectance have shown that in predominately water covered areas small increases in green leaf area emerging from the water can result in large increases in NDVI, which may be a factor driving greening in areas with standing water (Huemmrich *et al* 2021).

Over the 20 year time course of this study, some drier areas of the transect exhibited NDVI greening and in these cases NDVI change appeared to be related to changes in cover type with increased coverage of *Petasites* or *Vaccinium* (figures 6(a) and (b)). Shrubs are scarce in this tundra landscape, and increasing shrub area was not a factor in long term greening here (Harris *et al* 2021). Over this 20 year time period, vegetation changes associated with greening were not changes in plant functional type, such as a transition to shrubs, as have been observed in other locations (e.g. Myers-Smith *et al* 2011, Berner *et al* 2020). This suggests that the observed greening at this site is presently not leading to a different ecological state (i.e. a tipping point) and is expected to be reversable under different environmental conditions (Myers-Smith *et al* 2020).

NDVI browning was not related to change in species cover and appeared to be due to increased coverage of standing dead material in graminoid dominated canopies (figure 6(g) and (h)) (Huemmrich *et al* 2021). Repeated plot studies of vegetation cover have shown trends of increasing standing dead material in this region during the study period (Hollister *et al* 2015, Harris *et al* 2021). The effect of standing dead material may affect year to year variation in NDVI where dead material from growth in earlier productive years may act to decrease NDVI in later years (Barnhill *et al* 2023). In areas with standing water the water may obscure standing dead material and thus act to further enhance NDVI change in wet areas.

While looking for evidence of tundra response to climate change it is important to recognize that a significant fraction (34%) of the landscape showed no long term NDVI change outside of the expected year-to-year variation. Of the areas that did show significant responses (47% with increased NDVI, 19%with decreased NDVI), these changes appeared to be largely associated with the same microtopographic and hydrological effects that mediated the short term NDVI patterns in the original 2000–2002 study. Consequently, we propose that such microtopographic and hydrological effects can have a significant influence on multi-decadal NDVI trends in this arctic tundra environment.

5. Conclusion

The satellite data record provides important evidence of large scale tundra response to climate change. However, ground measurements that also cover multidecadal time periods provide critical information for the interpretation of the satellite data. In a region of tundra that is experiencing trends toward warmer and wetter conditions, we had the rare opportunity to re-measure NDVI across a 100 m transect after 20 years. There was strong spatial variability in NDVI and temporal change in NDVI at the scale of a meter. Microtopography influenced hydrology and species composition that affected the patterns of NDVI greening or browning, with complex patterns of change evident at the 1 m scale that can help explain the changes now emerging in the long-term MODIS satellite record. The transect data illustrate a variety of factors affecting NDVI change. Beyond its sensitivity to the amount of green vegetation we observed that NDVI appears to be affected by the presence of open water and standing dead vegetation in the field of view.

These field studies provide a valuable foundation for interpreting the larger view of surface changes provided by the several decades of satellite measurements. Continued advances including field portable spectrometers, unpiloted aerial vehicles and improved microtopographical mapping techniques will likely further improve our understanding of tundra change.

Data availability statements

MODIS data: ORNL DAAC (2018). MODIS and VIIRS Land Products Global Subsetting and Visualization Tool. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1379

Meteorology data: NOAA National Centers of Environmental Information www.ncei.noaa.gov/cdo-web/

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.3334/ORNLDAAC/2232.

Acknowledgments

Thanks to Stan Houston, Erica Anderson, and Jean Van Dalen for their work in collecting field measurements. We thank the Iñupiat people, on whose land this research was done. The original field measurements were funded by the International Arctic Research Center. This work is supported by NASA ABoVE Grants NNX17AC58A and 80NSSC19M0110.

Conflict of interest

The authors confirm that there are no relevant financial or non-financial competing interests to report.

ORCID iDs

K Fred Huemmrich https://orcid.org/0000-0003-4148-9108
John Gamon https://orcid.org/0000-0002-8269-7723
Petya Campbell https://orcid.org/0000-0002-0505-4951
Sergio Vargas Z https://orcid.org/0000-0002-0052-8580
Brenda Almanza https://orcid.org/0000-0002-8045-9334
Craig Tweedie https://orcid.org/0000-0002-3409-8881

References

Abolt C J, Young M H, Atchley A L and Harp D R 2018 Microtopographic control on the ground thermal regime in ice wedge polygons *Cryosphere* **12** 1957–68

Andresen C, Tweedie C E, Villarreal S, Cody R and Vargas Zesati S 2016 Detailed wetlands map for the Barrow Region, northern Alaska, for 2010–2013: barrow area information database (BAID) (Digital Media) (available at: http://barrowmapped.org)

Assmann J J, Myers-Smith I H, Kerby J T, Cunliffe A M and Daskalova G N 2020 Drone data reveal heterogeneity in tundra greenness and phenology not captured by satellites *Environ. Res. Lett.* **15** 125002

Barnhill K A, Roberts J M, Myers-Smith I, Williams M, Dexter K G, Ryan C, Wolfram U and Hennige S J 2023 Incorporating dead material in ecosystem assessments and projections *Nat. Clim. Change* **13** 113–5

Bayle A, Roy A, Dedieu J P, Boudreau S, Choler P and Lévesque E 2022 Two distinct waves of greening in northeastern Canada: summer warming does not tell the whole story *Environ. Res. Lett.* **17** 064051

Berner L T *et al* 2020 Summer warming explains widespread but not uniform greening in the Arctic tundra biome *Nat. Commun.* **11** 4621

Bhatt U S *et al* 2017 Changing seasonality of panarctic tundra vegetation in relationship to climatic variables *Environ. Res. Lett.* **12** 055003

Bhatt U S, Walker D, Raynolds M, Bieniek P, Epstein H, Comiso J, Pinzon J, Tucker C and Polyakov I 2013 Recent declines in warming and vegetation greening trends over pan-Arctic tundra *Remote Sens.* **5** 4229–59

Brown J, Everett K R, Webber P J, MacLean S F Jr and Murray D F 1980 The coastal tundra at Barrow *An Arctic Ecosystem: The Coastal Tundra at Barrow Alaska* ed J Brown, P C Miller, L L Tieszen and F L Bunnell (Dowden, Hutchinson & Ross, Inc.) pp 1–29

Callaghan T V, Cazzolla Gatti R and Phoenix G 2022 The need to understand the stability of arctic vegetation during rapid climate change: an assessment of imbalance in the literature *Ambio* **51** 1034–44

Didan K 2021 MOD13Q1 MODIS/terra vegetation indices 16-day L3 global 250 m SIN grid V061 (NASA EOSDIS Land Processes DAAC) (https://doi.org/10.5067/MODIS/MOD13Q1.061)

Epstein H E, Raynolds M K, Walker D A, Bhatt U S, Tucker C J and Pinzon J E 2012 Dynamics of aboveground phytomass of the circumpolar Arctic tundra during the past three decades *Environ. Res. Lett.* **7** 015506

Frost G V *et al* 2022 Tundra greenness, Arctic Report Card 2022 ed M L Druckenmiller, R L Thoman and T A Moon (https://doi.org/10.25923/g8w3-6v31)

Gamon J A, Huemmrich K F, Stone R S and Tweedie C E 2013 Spatial and temporal variation in primary productivity (NDVI) of coastal Alaskan tundra: decreased vegetation growth following earlier snowmelt *Remote Sens. Environ.* **129** 144–53

Gamon J A, Kershaw G P, Williamson S and Hik D S 2012 Microtopographic patterns in an arctic baydjarakh field: do fine-grain patterns enforce landscape stability? *Environ. Res. Lett.* **7** 015502

Goetz S J, Bunn A G, Fiske G J and Houghton R A 2005 Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance *Proc. Natl Acad. Sci. USA* **102** 13521–5

Guay K C, Beck P S A, Berner L T, Goetz S J, Baccini A and Buermann W 2014 Vegetation productivity patterns at high northern latitudes: a multi-sensor satellite data assessment *Glob. Change Biol.* **20** 3147–58

Harris J A *et al* 2021 Understanding the climate impacts on decadal vegetation change in northern Alaska *Arct. Sci.* **8** 1–21

Hollister R D, May J L, Kremers K S, Tweedie C E, Oberbauer S F, Liebig J A, Botting T F, Barrett R T and Gregory J L 2015 Warming experiments elucidate the drivers of observed directional changes in tundra vegetation *Ecol. Evol.* **5** 1881–95

Hollister R D, Webber P J and Tweedie C E 2005 The response of Alaskan arctic tundra to experimental warming: differences between short- and long-term responses *Glob. Change Biol.* **11** 525–36

Huang M *et al* 2017 Velocity of change in vegetation productivity over northern high latitudes *Nat. Ecol. Evol.* **1** 1649

Hubbard S S *et al* 2013 Quantifying and relating land-surface and subsurface variability in permafrost environments using LiDAR and surface geophysical datasets *Hydrogeol. J.* **1** 149–69

Huemmrich K F, Gamon J A, Tweedie C E, Campbell P K E, Landis D R and Middleton M 2013 Arctic tundra vegetation functional types based on photosynthetic physiology and optical properties *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **6** 265–75

Huemmrich K F, Gamon J A, Tweedie C E, Oberbauer S F, Kinoshita G, Houston S, Kuchy A, Hollister R D, Kwon H and Mano M 2010b Remote sensing of tundra gross ecosystem productivity and light use efficiency under varying temperature and moisture conditions *Remote Sens. Environ.* **114** 481–9

Huemmrich K F, Kinoshita G, Gamon J A, Houston S, Kwon H and Oechel W C 2010a Tundra carbon balance under varying temperature and moisture regimes *J. Geophys. Res. Biogeosci.* **115** G00I02

Huemmrich K F, Vargas Zesati S, Campbell P and Tweedie C 2021 Canopy reflectance models illustrate varying NDVI responses to change in high latitude ecosystems *Ecol. Appl.* **31** e02435

Jenkins L K, Barry T, Bosse K R, Currie W S, Christensen T, Longan S, Shuchman R A, Tanzer D and Taylor J J 2020 Satellite-based decadal change assessments of pan-Arctic environments *Ambio* **49** 820–32

Jia G J, Epstein H E and Walker D A 2009 Vegetation greening in the Canadian Arctic related to decadal warming *J. Environ. Monit.* **11** 2231

Ju J and Masek J G 2016 The vegetation greenness trend in Canada and US Alaska from 1984–2012 Landsat data *Remote Sens. Environ.* **176** 1–16

Kwon H J, Oechel W C, Zulueta R C and Hastings S J 2005 effects of climate variability on carbon sequestration among adjacent wet sedge tundra and moist tussock tundra ecosystems *J. Geophys. Res. Biogeosci.* **111** 2005–12

Lara M J, Nitze I, Grosse G, Martin P and McGuire A D 2018 Reduced arctic tundra productivity linked with landform and climate change interactions *Sci. Rep.* **8** 2345

Myers-Smith I H *et al* 2011 Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities *Environ. Res. Lett.* **6** 045509

Myers-Smith I H *et al* 2020 Complexity revealed in the greening of the Arctic *Nat. Clim. Change* **10** 106–17

Myneni R B, Keeling C D, Tucker C J, Asrar G and Nemani R R 1997 Increased plant growth in the northern high latitudes from 1981 to 1991 *Nature* **386** 698

ORNL DAAC 2018 MODIS and VIIRS land products global subsetting and visualization tool *Subset Obtained for MOD13Q1 Product at 71.322N,156.6029W, Time Period: 2000-01-01–2023-01-06, and subset size: 6.25 × 6.25 km* (ORNL DAAC) (Accessed 13 January 2023) (https://doi.org/10.3334/ORNLDAAC/1379)

Pattison R R, Jorgenson J C, Raynolds M K and Welker J M 2015 Trends in NDVI and tundra community composition in the Arctic of NE Alaska between 1984 and 2009 *Ecosystems* **18** 707–19

Raynolds M K, Walker D A, Epstein H E, Pinzon J E and Tucker C J 2012 A new estimate of tundra-biome phytomass from trans-Arctic field data and AVHRR NDVI *Remote Sens. Lett.* **3** 403–11

Riedel S M, Epstein H E and Walker D A 2005 Biotic controls over spectral reflectance of arctic tundra vegetation *Int. J. Remote Sens.* **26** 2391–405

Steltzer H and Welker J M 2006 Modeling the effect of photosynthetic vegetation properties on the NDVI–LAI relationship *Ecology* **87** 2765–72

Walker D A *et al* 2003 Phytomass, LAI, and NDVI in northern Alaska: relationships to summer warmth, soil pH, plant functional types, and extrapolation to the circumpolar Arctic *J. Geophys. Res. Atmos.* **108** 8169

Wang J A and Friedl M A 2019 The role of land cover change in Arctic-Boreal greening and browning trends *Environ. Res. Lett.* **14** 125007

Zhang Y, Song C, Band L E, Sun G and Li J 2017 Reanalysis of global terrestrial vegetation trends from MODIS products: browning or greening? *Remote Sens. Environ.* **191** 145–55