Terrestrial Ecosystems Summary

Section Coordinators: D. A. "Skip" Walker[1] and Mike Gill[2]

[1]University of Alaska Fairbanks, Fairbanks, AK, USA
[2]Canadian Wildlife Service, Environment Canada, Whitehorse, YT, Canada
& Conservation of Arctic Flora and Fauna (CAFF) / Circumpolar Biodiversity Monitoring Programme

November 10, 2011

The Terrestrial Ecosystem section of the 2012 Arctic Report Card illustrates the interconnections between the Arctic marine and terrestrial ecosystems. An example is the direct link between increases in Arctic tundra vegetation productivity and earlier peak productivity in many parts of the Arctic on one hand and increasing duration of the open water season and decreasing summer sea ice extent on the other (see the essay on *Sea Ice*).

The Normalized Difference Vegetation Index (NDVI) shows that there is a long-term trend of increased biomass production in many parts of the Arctic. Over the whole Arctic from 1982 to 2010, the maximum summer NDVI increased by an average of 8%. However, there is considerable spatial variability, ranging from a 26% increase in lands adjacent to the Beaufort Sea to a small decline in several areas. The areas of greatest increase appear to be correlated with adjacent coastal areas that have experienced dramatic retreats in summer sea ice extent (see the essay on *Sea Ice*). Despite these long-term trends, annual variation is significant. In 2009, circumpolar NDVI showed a dip that corresponded to elevated atmospheric aerosols and generally cooler summer temperatures over the Arctic. Then, in 2010, NDVI rebounded strongly in North America, but less so in Eurasia. Information from long-term ground-based observations shows that, in addition to increasing air temperatures and loss of summer sea ice, widespread greening is also occurring in response to other factors. These include landslides and other erosion features related to warming permafrost, tundra fires and factors related to increased human presence in the Arctic.

The impacts of increased biomass production in Arctic tundra ecosystems on arctic wildlife are unclear. Despite changes in tundra biomass, migratory barren-ground caribou appear to be within known ranges of natural variation, with many herds that have experienced declines in the past decade beginning to increase or stabilize. Despite this, rapid environmental and social changes in the Arctic are a concern.

Vegetation

D. A. Walker[1], U. S. Bhatt[2], T. V. Callaghan[3], J. C. Comiso[4], H. E. Epstein[5], B. C. Forbes[6], M. Gill[7], W. A. Gould[8], G. H. R. Henry[9], G. J. Jia[10], S. V. Kokelj[11], T. C. Lantz[12], S. F. Oberbauer[13], J. E. Pinzon[4], M. K. Raynolds[1], G. R. Shaver[14], C. J. Tucker[4], C. E. Tweedie[15], P. J. Webber[16]

[1]Institute of Arctic Biology, University of Alaska, Fairbanks, Fairbanks, AK, USA
[2]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, USA
[3]Royal Swedish Academy of Sciences, Abisko Naturvetenskapliga Station, Abisko, Sweden
[4]NASA Goddard Space Flight Center, Greenbelt, MD, USA
[5]Department of Environmental Sciences, University of Virginia, Charlottesville, VA, USA
[6]Arctic Centre, University of Lapland, Rovaniemi, Finland
[7]Environment Canada, Whitehorse, Canada
[8]USDA Forest Service, International Institute of Tropical Forestry, San Juan, PR
[9]Geography Department, University of British Columbia, Vancouver, BC, Canada
[10]RCE-TEA, CAS, Chinese Academy of Sciences, Institute for Atmospheric Physics, Beijing, China
[11]Water Resources Division, Indian and Northern Affairs Canada, Yellowknife, NWT, Canada
[12]University of Victoria, British Columbia, Canada
[13]Department of Biological Sciences, Florida International University, Miami, FL, USA
[14]Ecosystem Center, Marine Biological Laboratory, Woods Hole, MA, USA
[15]Department of Biology, The University of Texas at El Paso, El Paso, Texas, USA
[16]Department of Plant Biology, Michigan State University, East Lansing, MI, USA

November 10, 2011

Highlights

- The "greenness" of tundra vegetation has increased during the period of satellite observations (1982-2010) in Eurasia and North America.
- Increasing "greenness" is positively and significantly correlated with more abundant ice-free coastal waters and higher land temperatures over most of the Arctic region.
- A circum-Arctic dip in "greenness" in 2009 was a response to elevated atmospheric aerosols, including volcanic dust, and generally cooler summer temperatures across the Arctic. A circumpolar recovery occurred in 2010, and the mean NDVI for North America and the Northern Hemisphere overall was the greatest on record.
- In Eurasia, green-up is more rapid than in North America, and peak "greenness" in Eurasia occurred about 2 weeks earlier during 2000-2009 than in the 1980s.

Introduction

Circumpolar changes to tundra vegetation are currently being monitored from space using the Normalized Difference Vegetation Index (NDVI), an index of vegetation greenness. Maximum NDVI (MaxNDVI) was obtained each year from a 29-year (1982-2010) record of NDVI in a new NDVI dataset derived from the AVHRR sensors on NOAA weather satellites (Bhatt et al. 2010, Raynolds et al. 2012). In tundra regions the annual MaxNDVI usually occurs in early August and is correlated with above-ground biomass, gross ecosystem production, CO_2 fluxes and numerous other biophysical properties of tundra vegetation (Tucker et al. 1986; Stow et al. 2004). This essay describes MaxNDVI through to the end of 2010, the last complete year for which data are available.

Long-term circumpolar change in NDVI

MaxNDVI has increased during the period of satellite observations (1982-2010) in Eurasia and North America (Fig. TE1a), supporting model predictions that primary production of arctic tundra ecosystems will respond positively to increased summer warmth (Bhatt et al. 2008; Lawrence et al. 2008). Despite considerable spatial variation in the magnitude of change in each of the three variables (MaxNDVI, open water, summer warmth) examined, annual MaxNDVI patterns were also positively and significantly correlated with more abundant ice-free coastal waters (Fig. TE1a in this essay and Fig. SIO3 in the essay on *Sea Ice*) and higher tundra land temperatures (Fig. TE1b) over most of the Arctic region (Bhatt et al. 2010). However, some areas are showing negative trends in NDVI. The negative trends in NDVI in northern North America (e.g., northern Greenland and the Queen Elizabeth Islands of Canada) correspond to the areas with persistent summer-long coastal sea ice, while the areas of northern Russia with negative NDVI trends generally have decreasing land temperatures (Fig. TE1b).

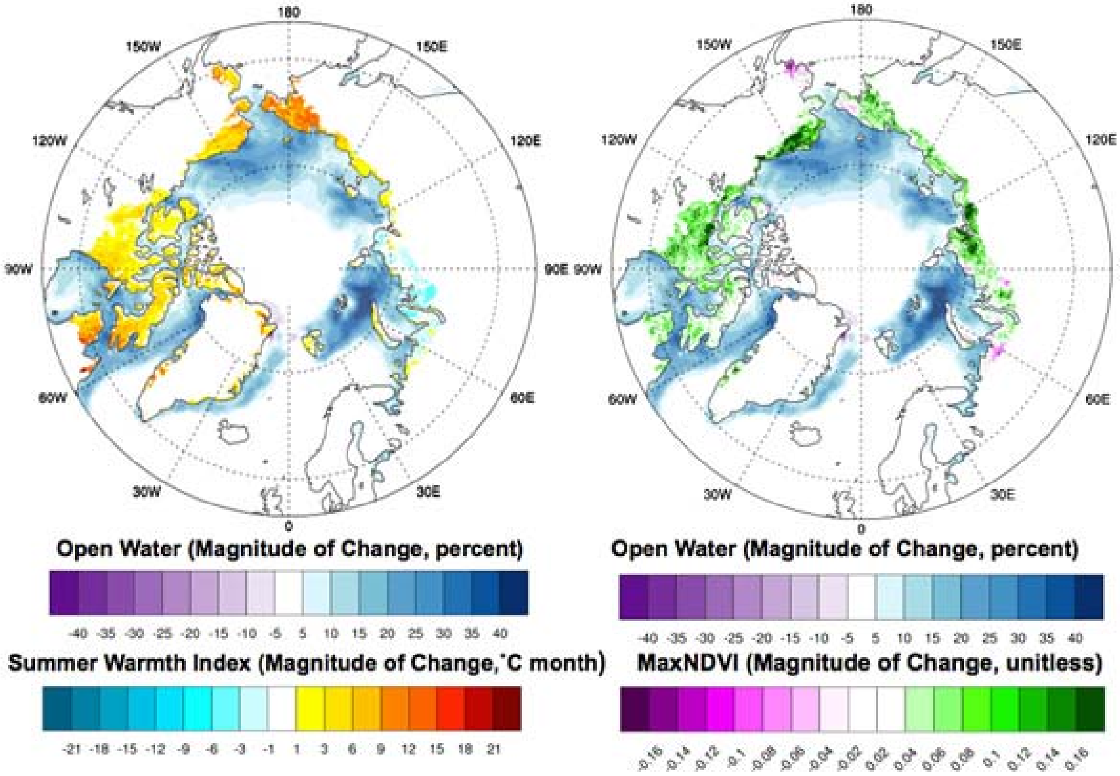

Fig. TE1. Trends for (a, right) summer (May-August) open water and annual MaxNDVI and (b, left) summer (May-August) open water and land-surface summer warmth index (SWI, the annual sum of the monthly mean temperatures >0 °C) derived from AVHRR thermal channels 3 (3.5-3.9 μm), 4 (10.3-11.3 μm) and 5 (11.5-12.5 μm). Trends were calculated using a least squares fit (regression) at each pixel. The total trend magnitude (regression times 29 years) over the 1982-2010 period is displayed.

Long-term, regional change in NDVI

Temporal changes in MaxNDVI for Arctic areas in Eurasia and North America show positive and nearly parallel increases amounting to a MaxNDVI increase of 0.02 NDVI units per decade (Fig. TE2a). However, there is considerable variability in the rate of increase in different regions of the Arctic. For example, the MaxNDVI increase adjacent to the Beaufort Sea (+26%) is the most rapid in the Arctic and corresponds to large changes in open water (+31%) and summer warmth index (17%). On the other hand, the MaxNDVI change in the western Kara Sea is among the smallest (+4.4%). corresponding to smaller changes in sea ice (+20%) and land temperatures (-6%) (Fig. TE2b). The sea-ice changes occurring in the eastern Kara Sea far exceed those elsewhere, but have not caused warming over adjacent lands or a major increase in MaxNDVI, as would have been expected. Instead, the adjacent land areas have cooled slightly and there is only a modest increase in NDVI. The causes are unknown, but might include greater summer cloudiness.

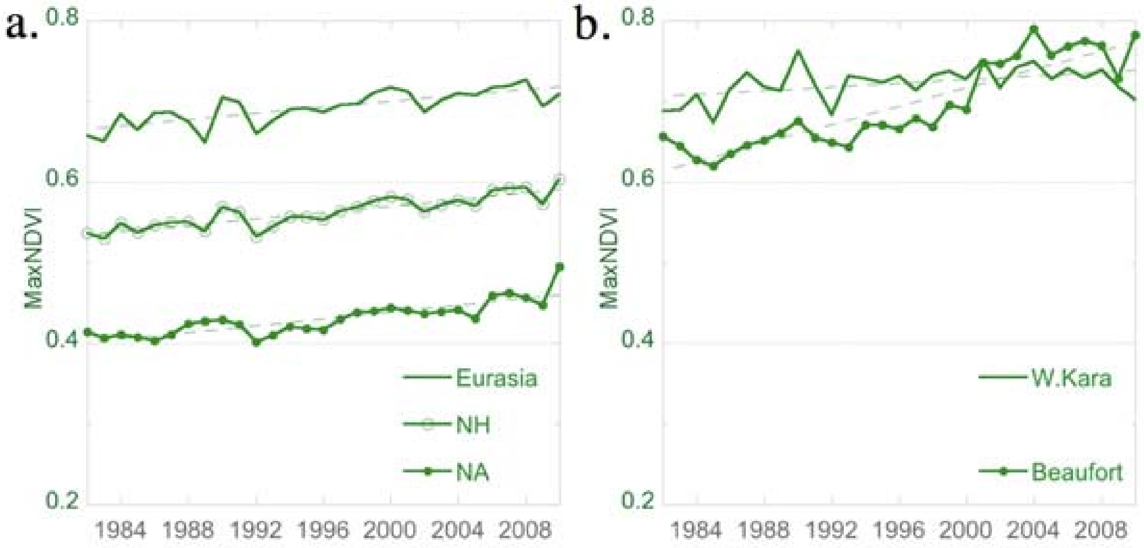

Fig. TE2. Time series of MaxNDVI during 1982-2010 for coastal tundra in (a) the Northern Hemisphere (NH) as a whole, Eurasia and North America, and (b) the western Kara Sea and Beaufort Sea.

In 2009 there was a circum-Arctic dip in NDVI (Fig. TE2) that corresponded to elevated atmospheric aerosols over the Arctic in the same year (Stone et al. 2010). This coincided with generally lower temperatures across the Arctic in 2009 and 2010. The elevated aerosols were attributed to an accumulation of pollutants from Eurasian industrial centers in the upper troposphere in combination with volcanic plumes from the eruption of Mt. Redoubt in Alaska. The enhanced Arctic haze in 2009 was estimated to reduce net shortwave irradiance by about 2-5 W m^{-2} (Stone et al., 2010).

NDVI and phenology

Bi-weekly NDVI data are used to show the yearly progression of the magnitude and timing of the photosynthetically-active period for the vegetation (Fig. TE3). Clear differences in phenological patterns occur in Eurasia and North America. Both areas show a ~0.06 unit MaxNDVI increase during the 29-yr record. In North America the curves show the increase in the MaxNDVI but no significant shift in timing of peak greenness. In Eurasia there is a somewhat more rapid green-up, and peak NDVI was reached about 2 weeks earlier during 2000-2009 than in the 1980s. This is consistent with Eurasian snow cover duration, which was stable during the 1980s and 1990s, but has declined rapidly since the early 2000s (see Fig. HTC3 in the essay on *Snow*). Neither North America nor Eurasia show a significant trend toward a longer growing season. However, whole-continent data appear to mask changes along latitudinal gradients and in different regions. For example, during 1982-2003, MaxNDVI along the Canadian Arctic climate gradient showed a ~1-week shift in the initiation of green-up and a somewhat higher NDVI late in the growing season in the Low Arctic (Jia et al. 2009). The High Arctic in Canada did not show earlier initiation of greenness, but did show a ~1-2 week shift toward earlier MaxNDVI.

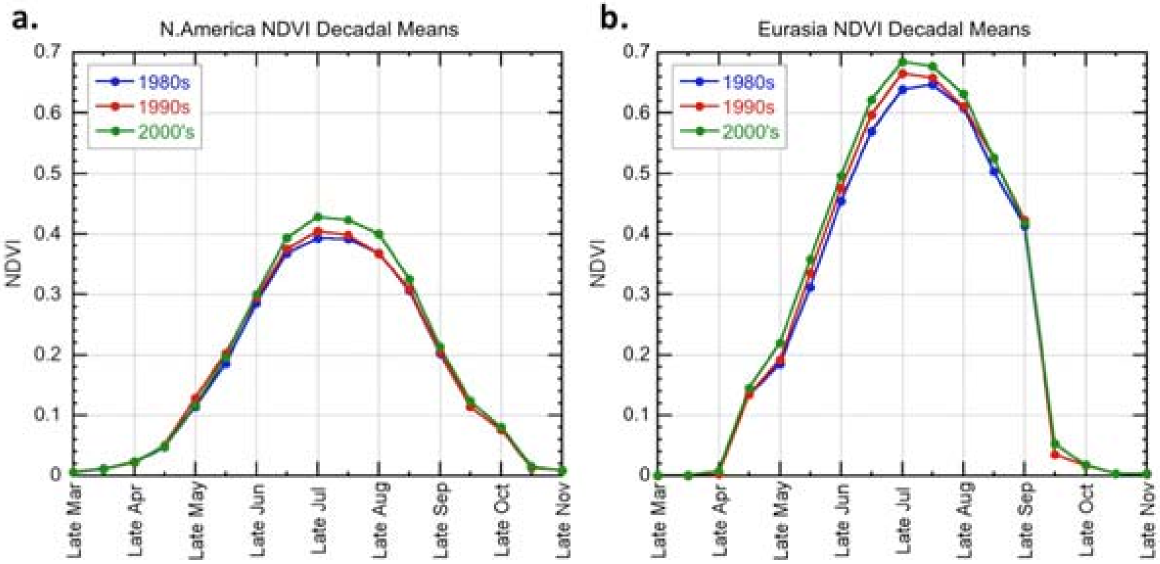

Fig. TE3. Decadal changes in NDVI-derived phenology in (a) Eurasia and (b) North America.

Field observations

The increased Arctic greening observed in the satellite data is also observed in long-term *in situ* vegetation measurements. For example, the International Tundra Experiment (ITEX), established in 1990, has made annual measurements of plant growth and phenology for up to 20 years using standardized protocols (Henry and Molau 1997). A recent synthesis of the long-term ITEX warming experiments has shown that effects on plant phenology differ by trait, community, and functional types (Elmendorf and Henry 2010). Some of these results indicate there have been increases in productivity consistent with warming (e.g. Hill and Henry 2011). In others, the links between local climate warming and vegetation change found in the NDVI data were not supported at the plot scale. There is a need for more careful evaluation of the causes of the observed changes, which may be driven by local, long-term, non-equilibrium factors other than climate warming, such as recovery from glaciation or changes in snow cover or precipitation (Troxler et al. 2010; Mercado and Gould 2010).

The Back to the Future (BTF) International Polar Year project, which revisited numerous Arctic research sites that were established between 15 to 60 years ago, is revealing decadal-scale changes. These include vegetation change and increases in plant cover at Barrow, Alaska, on Baffin Island and at multiple sites throughout Beringia (Tweedie et al. 2010). Advanced phenological development and species shifts associated with drying occurred on Disko Island, Greenland. Warming of permafrost was documented in sub-Arctic Sweden, and dramatic changes in pond water column nutrients, macrophyte cover and chironomid assemblages have been noted near Barrow. NDVI, gross ecosystem production, and methane efflux from wet vegetation types have increased at sites near Barrow, on Baffin Island and at the Stordalen mire in sub-Arctic Sweden. In most cases, air and ground warming appear to be the primary causes of change, but disturbances of various types are causing change at some sites. For example, at herbivore exclosures established at Barrow in the 1950s and 1970s it has been found that lemmings and other herbivores outside the exclosures had reduced the relative cover of lichens and graminoids and increased the relative cover of deciduous shrubs. Consequently, a wide variety of ecosystem properties, including thaw depth, soil moisture, albedo, NDVI, net ecosystem exchange and methane efflux were affected (Johnson et al. 2010). A warming Arctic will cause changes in species distributions and biodiversity in the Arctic. In response to these expected changes, the Circumpolar Biodiversity Monitoring Program is launching an integrated biodiversity monitoring plan for Arctic land, marine, coastal and freshwater ecosystems (Gill et al. 2008).

Other Arctic vegetation changes that are indirectly related to climate include those associated with landslides, thermokarst and fires, which are increasing in frequency in several regions of the Arctic (e.g., Goosef et al. 2009; Lantz et al. 2010a,b; Mack et al. 2011 in revision; Rocha and Shaver 2011). Higher soil temperatures, thawing permafrost, more abundant water and increased nutrients due to such disturbances result in pronounced greening often associated with more abundant shrub growth. Increasing air and ground temperatures are predicted to increase shrub growth in much of the Arctic, with major consequences for ecosystems (Lantz et al. 2010b). Several studies have observed increased shrub growth due to artificial warming, although the increases are small and frequently not statistically significant (e.g., Bret-Harte et al. 2003). On the other hand, there is growing evidence for increased shrub abundance at climatically- and anthropogenically-disturbed sites (Lantz et al. 2010a, b; Walker et al. 2011). In the Russian Arctic, erect deciduous shrub growth is closely associated with both the recent summer warming of ~2°C over more than half a century and a trend of increasing NDVI since 1981 (Forbes et al. 2010).

References

Bhatt, U. S, and co-authors, 2008: The atmospheric response to realistic reduced summer arctic sea ice anomalies. Geophysical Monograph Series 180, Arctic Sea Ice Decline: Observations, Projections, Mechanisms, and Implications, 91-110.

Bhatt, U. S. and co-authors, 2010: Circumpolar Arctic tundra vegetation change is linked to sea-ice decline. Earth Interactions, 14, 1-20.

Bret-Harte, M.S., G.R. Shaver, F.S. Chapin III. 2002: Primary and secondary stem growth in arctic shrubs: implications for community response to environmental change. Journal of Ecology 90: 251-267.

Elmendorf, S., G. Henry, and co-authors 2010: Assessments of recent tundra change based on repeated vegetation surveys. Abstract GC3B-05 presented at the 2010 Fall Meeting, AGU San Francisco CA, 13-17 Dec 2010.

Forbes, B.C., M. M. Fauria, and P. Zetterberg, 2010: Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows. Global Change Biology, 16, 1542-1554.

Gill, M.J., M.C. Raillard, C. Zockler and R.B. Smith. 2008: Developing an Integrated and Sustained Arctic Biodiversity Monitoring Network: The Circumpolar Biodiversity Monitoring

Program Five Year Implementation Plan. CAFF CBMP Report No. 14, CAFF International Secretariat, Akureyri, Iceland.

Gooseff, M. N., A. Balser, W. B. Bowden, and J. B. Jones, 2009: Effects of hillslope thermokarst in Northern Alaska. EOS, 90, 29-36.

Henry, G. H. R., and U. Molau, 1997: Tundra plants and climate change: the International Tundra Experiment (ITEX). Global Change Biology, 3 (Suppl. 1), 1-9.

Hill, G. B., and G. H. R. Henry, 2011: Responses of High Arctic wet sedge tundra to climate warming since 1980. Global Change Biology, 17, 276-287.

Hudson, J. M. G., and G. H. R. Henry, 2009: Increased plant biomass in a High Arctic heath community from 1981 to 2008. Ecology, 90, 2657-2663.

Jia, G. J., H. E. Epstein, and D. A. Walker, 2009: Vegetation greening in the Canadian Arctic related to decadal warming. Journal of Environmental Monitoring, 11, 2231-2238.

Johnson, D. R., M. J. Lara, G. R. Shaver, and C. Tweedie, 2010: Herbivory and soil moisture drive long-term patterns of vegetation structure and function in Alaskan coastal tundra: results from resampling historic exclosures at Barrow. Abstract GC43B-0908 presented at 2010 Fall Meeting, AGU, San Francisco, CA, 13-17 Dec 2010.

Lantz, T. C., S. E. Gergel, and G. H. R. Henry, 2010a: Response of green alder (*Alnus viridis subsp fruticosa*) patch dynamics and plant community composition to fire and regional temperature in north-western Canada. Journal of Biogeography, 37, 1597-1610.

Lantz, T. C, S. E. Gergel, and S. V. Kokelj. 2010b. Spatial heterogeneity in the shrub tundra ecotone in the Mackenzie Delta region, Northwest Territories: Implications for Arctic environmental change. Ecosystems, 13, 194-204.

Lawrence, D. M., A. G. Slater, R. A. Tomas, M. M. Holland, and C. Deser, 2008: Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss. Geophysical Research Letters, 35: L11506, doi:10.1029/2008GL033985.

Mack, M. C., M. S. Bret-Harte, T. N. Hollingsworth, R. R. Jandt, E. A. G. Schuur, G. R. Shaver, D. L. Verbyla. Novel wildfire disturbance and carbon loss from arctic tundra. Nature, in revision.

Mercado-Diaz, J. A., and W. A. Gould, 2010: Landscape- and decadal scale changes in the composition and structure of plant communities in the northern foothills of the Brooks Range of Arctic Alaska. Abstract GC43B-0982 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec.

Overland, J., M. Wang, and J. Walsh, 2011: Atmosphere. 2010, BAMS Report This volume.

Raynolds, M.K., D.A. Walker, H.E. Epstein, J.E. Pinzon and C.J. Tucker. 2012. A new estimate of tundra-biome phytomass from trans-Arctic field data and AVHRR NDVI. Remote Sensing Letters, 3, 403-411.

Rocha, A., and G. R. Shaver. 2011. Burn severity influences post-fire CO2 exchange in arctic tundra. Ecological Applications, doi:10.1890/10-0255.1.

Stone, R. S., and co-authors, 2010: A three-dimensional characterization of Arctic aerosols from airborne Sun photometer observations PAM-ARCMIP, April 2009. Journal of Geophysical Research, 115, D13203, doi:10.1029/2009JD013605.

Stow, D. A., and coauthors. 2004: Remote sensing of vegetation and land-cover change in arctic tundra ecosystems. Remote Sensing of Environment, 89: 281-308.

Tucker, C. J., I. Y. Fung, D. C. Kealing, and R. H. Gammon, 1986: Relationship between atmospheric CO_2 variations and a satellite derived vegetation index. Nature, 319, 195-199.

Troxler, T. G., and co-authors. 2010: Long-term phenological changes in tundra plants in response to experimental warming using the International Tundra Experiment (ITEX) Network. Abstract COS 93-10, 95th ESA Annual Meeting, Pittsburg, PA, 1-6 Aug 2010.

Tweedie, C.E., and co-authors, 2010: Decadal time scale change in terrestrial plant communities in North America arctic and alpine tundra: A contribution to the International Polar Year Back to the Future project. Abstract GC53B-03 presented at 2010 Fall Meeting, AGU, San Francisco, CA, 13-17 Dec 2010.

Walker, D.A., and co-authors, 2010: Vegetation: Special Supplement to Bulletin of the American Meteorological Society, 91, S115-S116.

Walker. D. A., and co-authors, 2011: Cumulative effects of rapid land-cover and land-use changes on the Yamal Peninsula, Russia. Eurasian Arctic Land Cover and Land Use in a Changing Climate, Gutman, G., and Reissel, A., Eds., Springer, 206-236.