## e. *Land*

### 1) Vegetation—D. A. Walker, U. S. Bhatt, J. C. Comiso, H. E. Epstein, W. A. Gould, G. H. R. Henry, G. J. Jia, S. V. Kokelj, T. C. Lantz, J. A. Mercado-Díaz, J. E. Pinzon, M. K. Raynolds, G. R. Shaver, C. J. Tucker, C. E. Tweedie, and P. J. Webber

The summer greenness of Arctic tundra vegetation as measured using the maximum Normalized Difference Vegetation Index (MaxNDVI) has generally increased during the period 1982–2008 (Fig. 5.15). Changes in MaxNDVI are much greater in North America (9% increase) than Eurasia (2%). Coherent temporal relationships between near coastal sea ice, summer tundra land surface temperatures, and vegetation productivity have been demonstrated using Advanced Very High Resolution Radiometer (AVHRR)-derived 3g NDVI data (Pinzon et al. 2009, manuscript submitted to *EOS, Trans. Amer. Geophys. Union*; Bhatt et al. 2009, manuscript submitted to *Earth Interactions*). Absolute MaxNDVI changes are by far the greatest in the northern Alaska/Beaufort Sea area (0.09 AVHRR NDVI units), whereas the percentage changes have been highest in the Baffin Bay, Beaufort Sea, Canadian Archipelago, and Davis Strait areas (10–15% changes) (Fig. 5.15). The changes in NDVI are positively and significantly correlated with changes in summer Arctic land surface temperatures. Yearly variations in summer land temperatures are strongly and negatively correlated with yearly variations in the summer coastal sea ice (Bhatt et al. 2009, manuscript submitted to *Earth Interactions*). These observations support model projections that the Arctic land surfaces should warm as a result of the reduced summer extent of sea ice (Bhatt et al. 2008; Lawrence et al. 2008) and furthermore indicate that tundra ecosystems are responding to the increased summer warmth. Changes in the timing of tundra green up and senescence are also occurring. Green up is earlier in the cold sparsely vegetated high latitudes, whereas a shift to a longer green season is occurring during the fall in the more continuously vegetated southern Arctic (Jia et al. 2009). These changes are evident through the analysis of NOAA AVHRR satellite data in the Canadian Arctic for the period 1982–2003.

The greening trends observed in the satellite data are now supported by quantitative, long-term in situ vegetation measurements from the International Tundra Experiment (ITEX) and the Back to the Future (BTF) projects. As in the satellite measurements, the most evident changes appear to be occurring first in the sparsely vegetated areas of the far North. A study of plots at Alexandra Fiord, Ellesmere Island, is the first to demonstrate significant changes in above and below ground biomass over the last 25–30 years (Hill and Henry 2010; Hudson and Henry 2009) (Fig. 5.16). In addition, there has been a change in the relative abundance of species with an increase in the dominant species over this same time period. The changes in the tundra plant communities are most likely in response to the increase in temperature over the past 35 years of between 0.6°C–1.0°C per decade, with the strongest increases seen in the winter temperatures. The increases in biomass also correspond with longer growing seasons, with extensions into the late summer and with deeper active layers (depth of summer soil thawing). In another far-north Canada study, repeat photographs of permanent vegetation study plots 46 years after their initial installation near the Lewis Glacier, Baffin Island, document rapid vegetation changes along the margins of large retreating glaciers (Johnson et al. 2009b; P. J. Webber and C. E. Tweedie 2009, personal communication).

Further south, in the more lush tundra near Toolik Lake, a detailed analysis of a 20-year record (1989–2008) of tundra vegetation structure and composition from a set of 156 permanent monitoring plots indicates a general increase in above ground biomass (Gould and Mercado-Díaz 2008). Over the last two decades the relative abundance of vascular vegetation increased by 16%, while the relative abundance of nonvascular vegetation decreased by 18%. The canopy height, as well as the extent and complexity of the canopy have been increasing over time with the amount of horizontal surface having multiple strata increasing from about 60% to 80%.

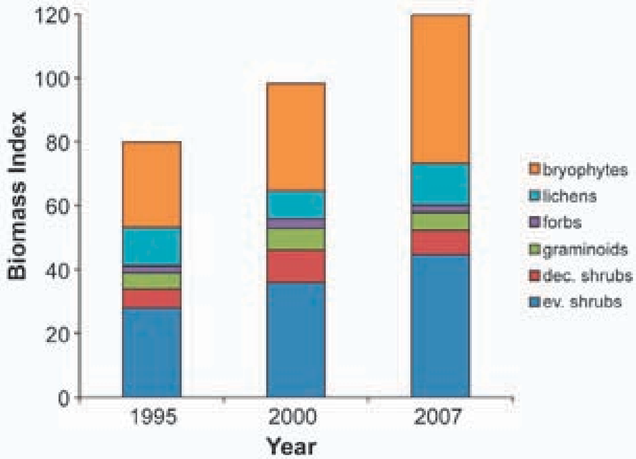

**Fig. 5.16. Above ground biomass index by plant functional type for 18 permanent vegetation plots at Alexandra Fiord, Ellesmere Island, Canada, in 1995, 2000, and 2007. Values were the mean number of living tissue hits per plot using the point intercept method. Total live vegetation, bryophytes, and evergreen shrubs increased significantly over the period at p = 0.05. (Hudson and Henry 2009).**

The frequencies of landslides, thermokarst features (irregular land surfaces formed in permafrost regions by melting ground ice), and fires have been noted in several areas of the Arctic (B. Jones et al. 2009; Kokelj et al. 2009; Lantz 2008; Lantz and Kokelj 2008; Walker et al. 2009; Leibman and Kizyakov 2007; Ukraientseva 2008). Warmer soil temperatures, melting permafrost, more abundant water, and increased nutrients on these features result in their pronounced greening.

In late summer 2007, the Anaktuvuk River fire near the University of Alaska's Toolik Lake Field Station burned almost 1000 km$^2$. It is the largest known fire to occur in northern Alaska and offered an opportunity for detailed analysis of the changes to the tundra energy and nutrient balance (Liljedahl et al. 2007) and spectral properties (Rocha and Shaver 2009). The burning itself released ~1.9 million metric tons of carbon to the atmosphere, which was about 30% of the carbon stock within the vegetation and active layer of this area (M. C. Mack, unpublished data).

### 2) PERMAFROST—V. Romanovsky, N. Oberman, D. Drozdov, G. Malkova, A. Kholodov, S. Marchenko

Observations show a general increase in permafrost temperatures during the last several decades in Alaska (Romanovsky et al. 2002; Romanovsky et al. 2007; Osterkamp 2008), northwest Canada (Couture et al. 2003; Smith et al. 2005), Siberia (Oberman and Mazhitova 2001; Oberman 2008; Drozdov et al. 2008; Romanovsky et al. 2008), and Northern Europe (Isaksen et al. 2000; Harris and Haeberli 2003).

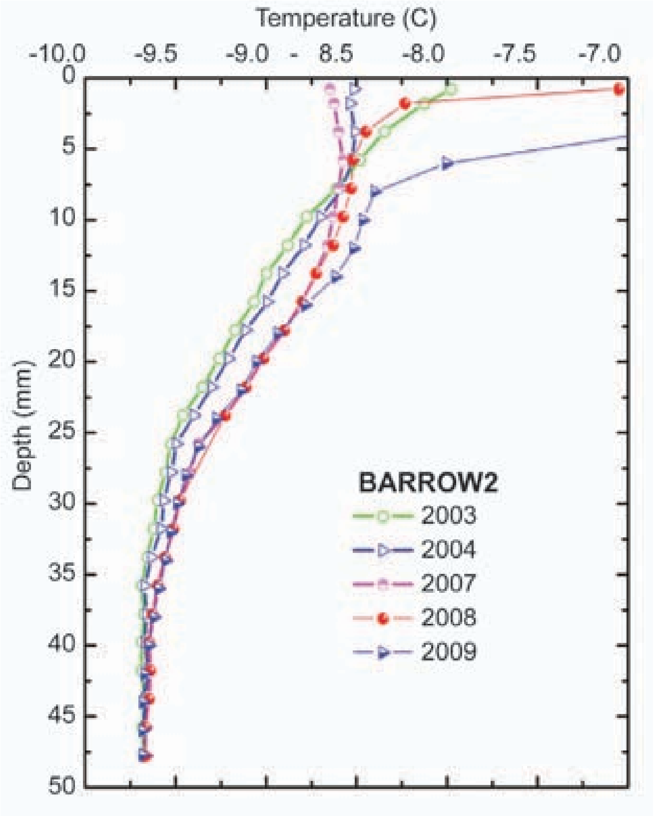

**FIG. 5.17. Changes in permafrost temperature at different depths at the Barrow, Alaska, Permafrost Observatory in 2002–09.**

Most of the permafrost observatories in Alaska show a substantial warming during the 1980s and 1990s. The detailed characteristic of the warming varies between locations but is typically from 0.5°C to 2°C at the depth of zero seasonal temperature variations in permafrost (Osterkamp 2008). However, during the last nine years, the permafrost temperature has been relatively stable on the North Slope of Alaska. There was even a slight decrease in the Alaskan Interior during the last three years. Only coastal sites in Alaska still show continuous warming, especially during the last three to four years (Fig. 5.17).

Permafrost temperature has increased by 1°C to 2°C in northern Russia during the last 30 to 35 years. A common feature for Alaskan and Russian sites is more significant warming in relatively cold permafrost than in warm permafrost in the same geographical area. An especially noticeable permafrost temperature increase in the Russian Arctic was observed during the last three years—the mean annual permafrost temperature at 15m depth increased by more than 0.35°C in the Tiksi area and by 0.3°C at 10m depth in the European North of Russia.

The last 30 years of increasing permafrost temperatures have resulted in the thawing of permafrost in areas of discontinuous permafrost in Russia (Oberman 2008). This is evidenced by changes in the depth and number of taliks (a layer of year-round unfrozen ground that lies in permafrost), especially in sandy and sandy loam sediments compared to clay. A massive development of new closed taliks in some areas of the continuous permafrost zone, as a result of increased snow cover and warming permafrost, was responsible for the observed northward movement of the boundary between continuous and discontinuous permafrost by several tens of kilometers (Oberman and Shesler 2009).

### 3) RIVER DISCHARGE—A. Shiklomanov

Annual river discharge to the Arctic Ocean from the major Eurasian rivers in 2008 was 2078 km$^3$ (Fig. 5.18). In general, river discharge shows an increasing trend over 1936–2008 with an average rate of annual change of 2.9 ± 0.4 km$^3$ yr$^{-1}$. An especially intensive increase in river discharge to the ocean was observed during the last 20 years when the sea ice extent in the