# Tundra Greenness

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## Headlines

- In 2024, the circumpolar mean maximum tundra greenness value was the second highest in the high-resolution 25-year MODIS satellite record, continuing a sequence of record or near-record high values since 2020.
- Tundra greenness reached a record high value over the North American Arctic, while the value in the Eurasian Arctic was sixth highest in the MODIS record.
- The "greening of the Arctic," first reported in the late 1990s as an increase in the productivity and abundance of tundra vegetation due to rapid warming and sea-ice decline, is an ongoing phenomenon evident in all available long-term satellite records.

## Introduction

The Arctic tundra biome occupies Earth's northernmost lands, covering a 5.1 million $km^2$ area that encircles the Arctic Ocean and is bound to the south by the boreal forest biome (Raynolds et al. 2019). Arctic tundra ecosystems are experiencing profound changes as vegetation and underlying permafrost soils are strongly influenced by rising air temperatures and the rapid decline of sea ice (see essays *Surface Air Temperature* and *Sea Ice*). By the late 1990s, an increase in the productivity of tundra vegetation became evident in global satellite observations, a phenomenon that continued and soon became known as "the greening of the Arctic." Arctic greening is dynamically linked with Earth's changing climate, seasonal snow, permafrost, and sea-ice cover, and remains a focus of multi-disciplinary scientific research.

## Spaceborne monitoring of Arctic tundra greenness

Global vegetation has been monitored from space since late 1981 with the launch of the Advanced Very High Resolution Radiometer (AVHRR) sensor. In 2000, the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Landsat series of satellites began providing complementary circumpolar greenness records with higher spatial resolution and improved calibration. All of these instruments monitor vegetation greenness using the Normalized Difference Vegetation Index (NDVI), a spectral metric that exploits the unique way in which vegetation absorbs and reflects visible and infrared light.

Both AVHRR and MODIS have recorded increasing annual maximum tundra greenness (MaxNDVI) across most of the circumpolar Arctic during 1982-2023 and 2000-24, respectively (Figs. 1a,b). Both records display widespread greening trends in Low Arctic Eurasia and North America, except for portions of southwestern Alaska, and central and northeastern Siberia where flat or negative ("browning") trends are evident. Trends in the High Arctic—particularly the Canadian Arctic Archipelago—are mixed between the two satellite records, which may be partly due to their different observational periods, as well as observational challenges posed by the very short growing season, persistent cloudiness, and high interannual variability in snowmelt and surface water in these environments (Karlsen et al. 2024). Regional contrasts in greening highlight the complexity of Arctic change and the rich web of interactions that exist between tundra ecosystems and the local properties of sea ice, permafrost, seasonal snow (see essay *Terrestrial Snow Cover*), soil composition and moisture, microtopography, disturbance processes, wildlife, and human activities (Heijmans et al. 2022; Tassone et al. 2024). Understanding the underlying drivers of complex Arctic trends is important for improved monitoring and prediction of tundra ecosystem functions and the consequences of Arctic change on the global carbon cycle (see essay *Carbon Cycling*).

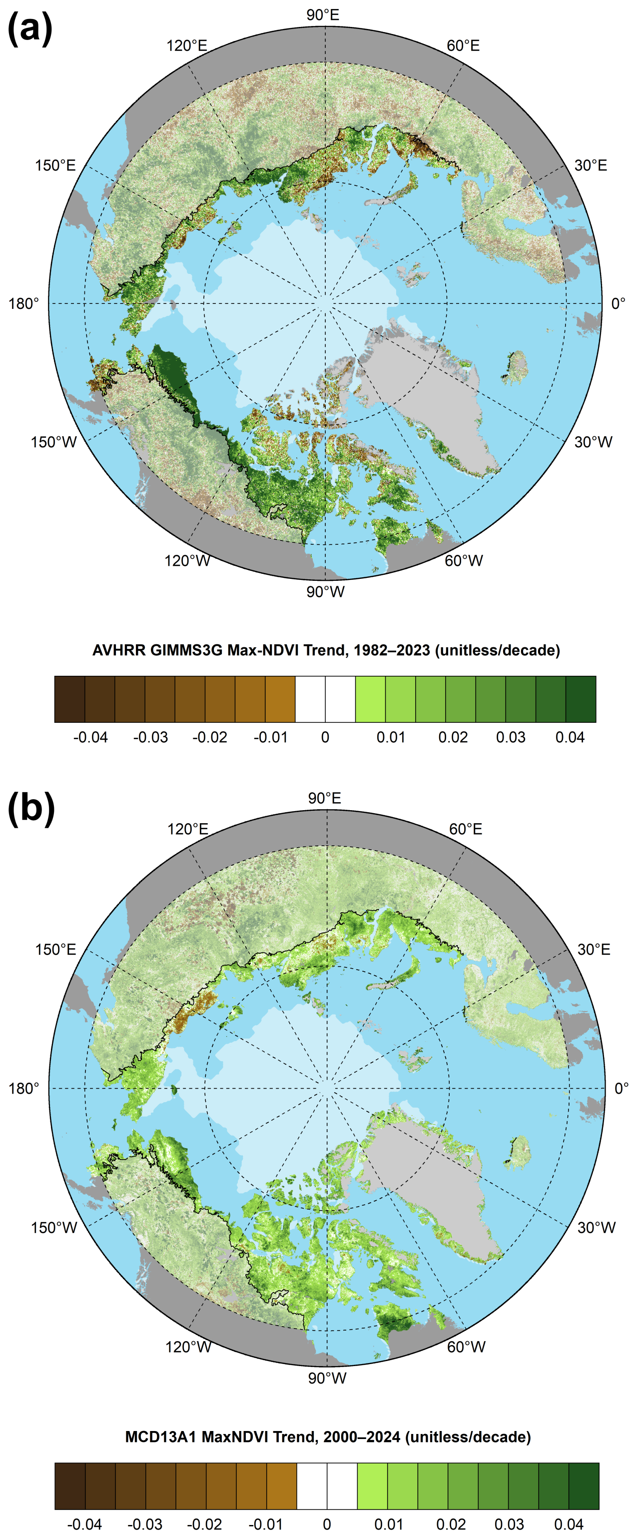


**Fig. 1.** Magnitude of the MaxNDVI trend calculated as the change per decade using ordinary least squares regression for Arctic tundra (solid colors), and boreal forest north of 60° latitude (muted colors) during (a) 1982-2023 based on the AVHRR GIMMS 3-g+ dataset, and (b) 2000-24 based on the MODIS MCD13A1 v6.1 dataset. In each panel, the circumpolar treeline is indicated by a black line, and the 2024 mean August sea-ice extent is indicated by light shading.

The neighboring boreal forest biome (see Fig. 1a,b) occupies large swaths of northern Eurasia and North America, and has also emerged as a focal point of global environmental change. Patches of positive and negative greenness trends are widely interspersed, reflecting complex interactions among the biome's active wildfire regime, climate change, permafrost thaw, extreme events, pathogens, and other factors (Kim et al. 2024). Browning has generally prevailed in the warmer southern boreal zone (Berner and Goetz 2022), but greening has been widespread along the forest-tundra ecotone in the north, often in association with tall shrub and tree expansion (Wong et al. 2024).

At the time of writing, MaxNDVI data for 2024 were only available for MODIS. In 2024, the MODIS observed circumpolar average MaxNDVI value was slightly higher (0.9%) compared to 2023 and represents the second highest in the 25-year record for that sensor. This continued a sequence of record or near-record high values that began in 2020, with the four highest MaxNDVI values in the 25-year MODIS record being observed since that year. Tundra greenness reached a new record high value in the North American Arctic, and was much higher than normal in northern Alaska, central and eastern Canada, and Greenland (Fig. 2). Localized areas of lower-than-normal greenness in Canada's Northwest Territories were likely the result of intense wildfire activity in 2023 and 2024. The Eurasian Arctic, however, featured a mixture of positive and negative departures from normal, a pattern that was also evident in summer 2023. Interestingly, while some of the Eurasian regions with below normal MaxNDVI also experienced cooler than normal summer temperatures (e.g., easternmost Chukchi Peninsula), others experienced very warm conditions (e.g., north-central Siberia), complicating the degree to which greening can be attributed simply to warmer summer temperatures (see essay *Surface Air Temperature*). Negative anomalies in northeastern Siberia could partly reflect the highly active fire season in that region. Nonetheless, the long-term trend in MODIS-observed tundra greenness is strongly positive (greening) for most of the circumpolar region. Although 2024 data are not yet available for AVHRR, this dataset also corroborates the MODIS record, with the three highest MaxNDVI values in the 42-year AVHRR record all observed since 2020 (Fig. 3).

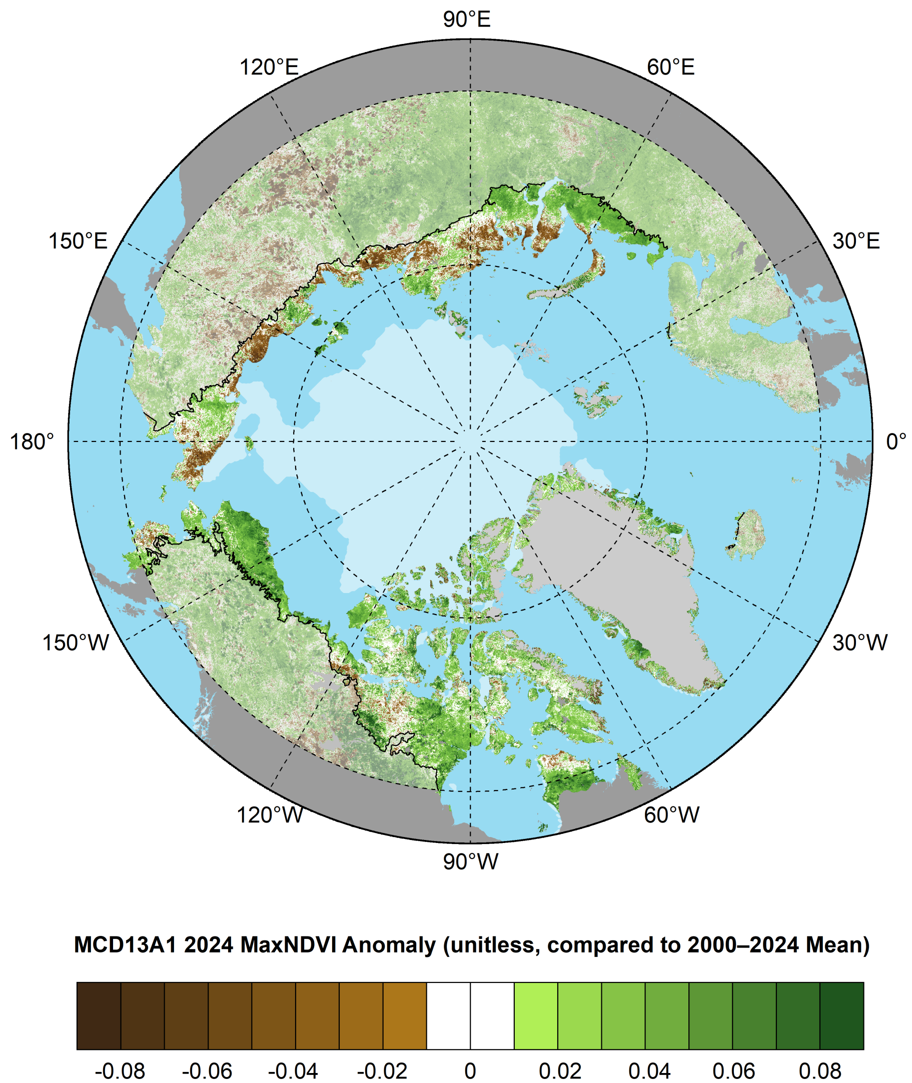


**Fig. 2.** Circumpolar MaxNDVI anomalies for the 2024 growing season relative to mean values (2000-24) from the MODIS MCD13A1 v6.1 dataset. The 2024 mean August sea-ice extent is indicated by light shading.

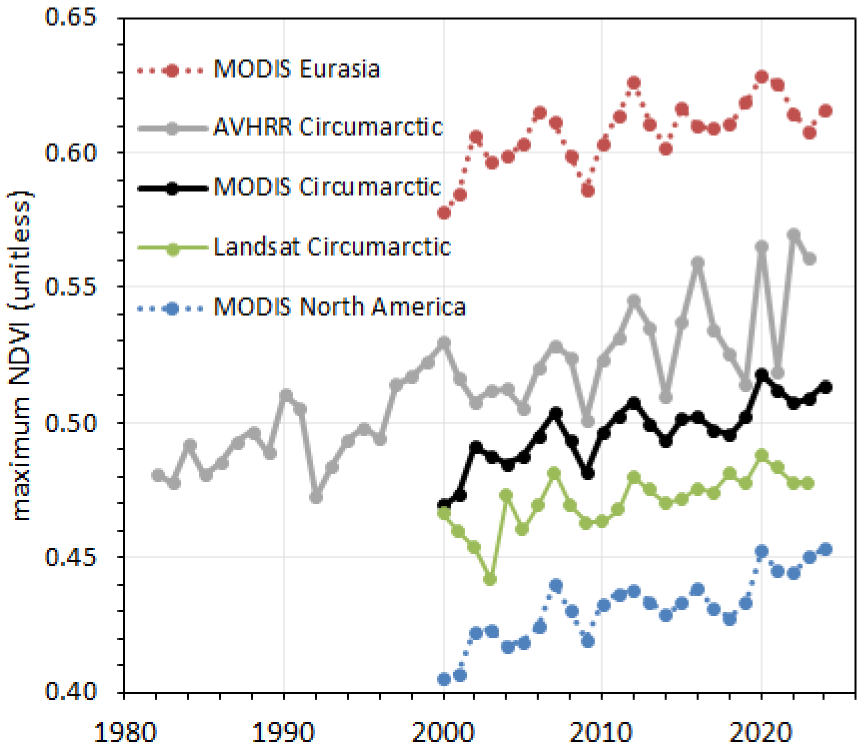


**Fig. 3.** Time-series of mean MaxNDVI for Arctic tundra from the MODIS MCD13A1 v6.1 (2000-24) dataset for the Eurasian Arctic (red), North American Arctic (blue), and the circumpolar Arctic (black), and from the AVHRR GIMMS-3g+ (1982-2023; gray) and Landsat Collection 2 (2000-23; green) datasets.

## Drivers and consequences of Arctic greening

A widely recognized manifestation of Arctic greening is *shrubification*—an increase in the cover, height, and biomass of tundra shrubs such as willows, birches, and alders (Fig. 4), which have higher NDVI than low-growing tundra plants. Newly developed tall shrubs create complex vertical structure and foraging opportunities that have supported the northward expansion of boreal mammals and birds in recent decades (Tape et al. 2022). On the other hand, shrubs tend to crowd out low-growing tundra plants, particularly lichens, which are an important part of the diet of caribou (Ramirez et al. 2024; see essay *Western Arctic Caribou Herd*).

**Fig. 4.** A major driver of circumpolar greening trends is the expansion of tall, canopy-forming shrubs, such as alder (upper left and upper right). Increases in the cover and height of shrubs have far-reaching effects on Arctic ecosystems and can reduce the abundance of other tundra plants, particularly of lichens (lower left) which provide important forage for caribou and reindeer. Field-based efforts to monitor Arctic ecosystems (lower right) are critical to understanding the drivers and consequences of Arctic greenness trends. Photos are from the Seward Peninsula, western Alaska, July 2024 (credit G. V. Frost).

Arctic greenness trends are influenced by a complex set of interacting climatic and environmental drivers and the dynamics evident in satellite time-series reflect many sources of interannual and decadal variability. Interannual variability in snow cover and subsequent impacts on plant phenology, productivity, and soil hydrology further complicate the greening and browning signals (Bennett et al. 2022). Persistent summer cloudiness can also lead to the underestimation of MaxNDVI in certain years and locations, potentially masking the greening trend. Ground-based monitoring is therefore essential to understand the causes and consequences of Arctic greening and browning (Fig. 4), something that is challenging to standardize across multiple observers and areas of the Arctic, but for which standard protocols are now being made (CAFF 2024). Nonetheless, the sequence of record or near-record MaxNDVI values observed in multiple satellite datasets since 2020 provides strong evidence that the overall cover and biomass of vegetation in the Arctic tundra biome are without historic precedent, and likely exceeds that of any period since at least the "Little Ice Age," a period of cool global temperatures that ended in the late 19th century.

## Methods and data

The satellite record of Arctic tundra greenness began in 1982 using AVHRR, a sensor that collects daily observations and continues to operate onboard polar-orbiting satellites. We also report observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Landsat series of satellites, which are modern systems that provide circumpolar greenness observations since 2000. MODIS is nearing the end of its service life, but continuity of this important record will be maintained by its successor, the Visible Infrared Imaging Radiometer Suite (VIIRS). At the time of writing, data for the 2024 growing season were not fully processed for AVHRR and Landsat, so we report on 2024 conditions using MODIS only. The long-term AVHRR dataset analyzed here for 1982-2023 is the Global Inventory Modeling and Mapping Studies 3g V1.2 dataset (GIMMS-3g+), which is based on corrected and calibrated AVHRR data with a spatial resolution of about 8 km (Pinzon et al. 2023). For MODIS, we computed tundra greenness trends for 2000-24 with a higher spatial resolution of 500 m, combining 16-day Vegetation Index products from Terra (MOD13A1, version 6.1) and Aqua (MYD13A1, version 6.1) (Didan 2021a,b), referred to here as MCD13A1. Landsat provides tundra greenness data at a much higher spatial resolution of 30 m; we computed time-series of greenness from Landsat Collection 2 (Crawford et al. 2023) using the methods of Berner and Goetz (2022). Circumpolar maps depicting greenness trends (AVHRR and MODIS only) cover the Arctic tundra biome, as well as boreal forest and non-Arctic tundra above 60° N latitude. For time-series plots, data were masked to include only ice-free land within the extent of the Circumpolar Arctic Vegetation Map (Raynolds et al. 2019). MODIS and Landsat data were further masked to exclude permanent water based on the 2015 MODIS Terra Land Water Mask (MOD44W, version 6). We summarize the GIMMS-3g+, MODIS, and Landsat records for Maximum NDVI (MaxNDVI), the peak yearly value that is typically observed during the months of July and August.

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