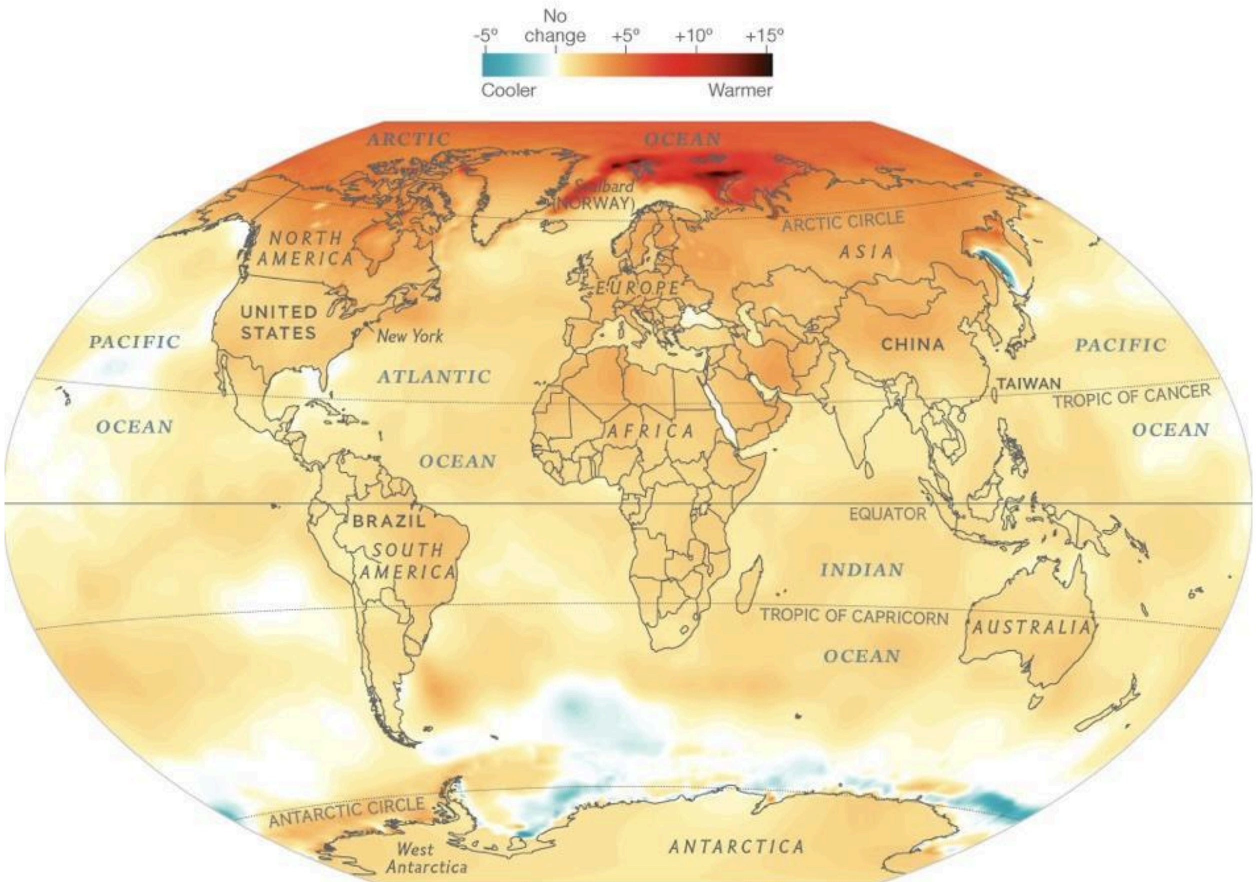
ARCTIC GREENING: IS THE GLASS HALF-FULL?

68% of Earth's landmass is in the northern hemisphere, and 50% of Earth's landmass is north of 30-degree latitude. It is also the area where the most severe global warming is occurring.



High Latitudes (60° to 90° North & South), especially the Arctic, are the fastest-warming areas on Earth. This phenomenon, called *polar amplification*, occurs because as ice melts, it exposes darker ocean and land surfaces that absorb more sunlight rather than reflect it.

Mid-Latitudes (30° to 60° North & South) are temperate zones experiencing steady, pronounced warming that exceeds the global average, particularly across large landmasses. Europe and Central Asia are the notable hotspots within the Northern Hemisphere.

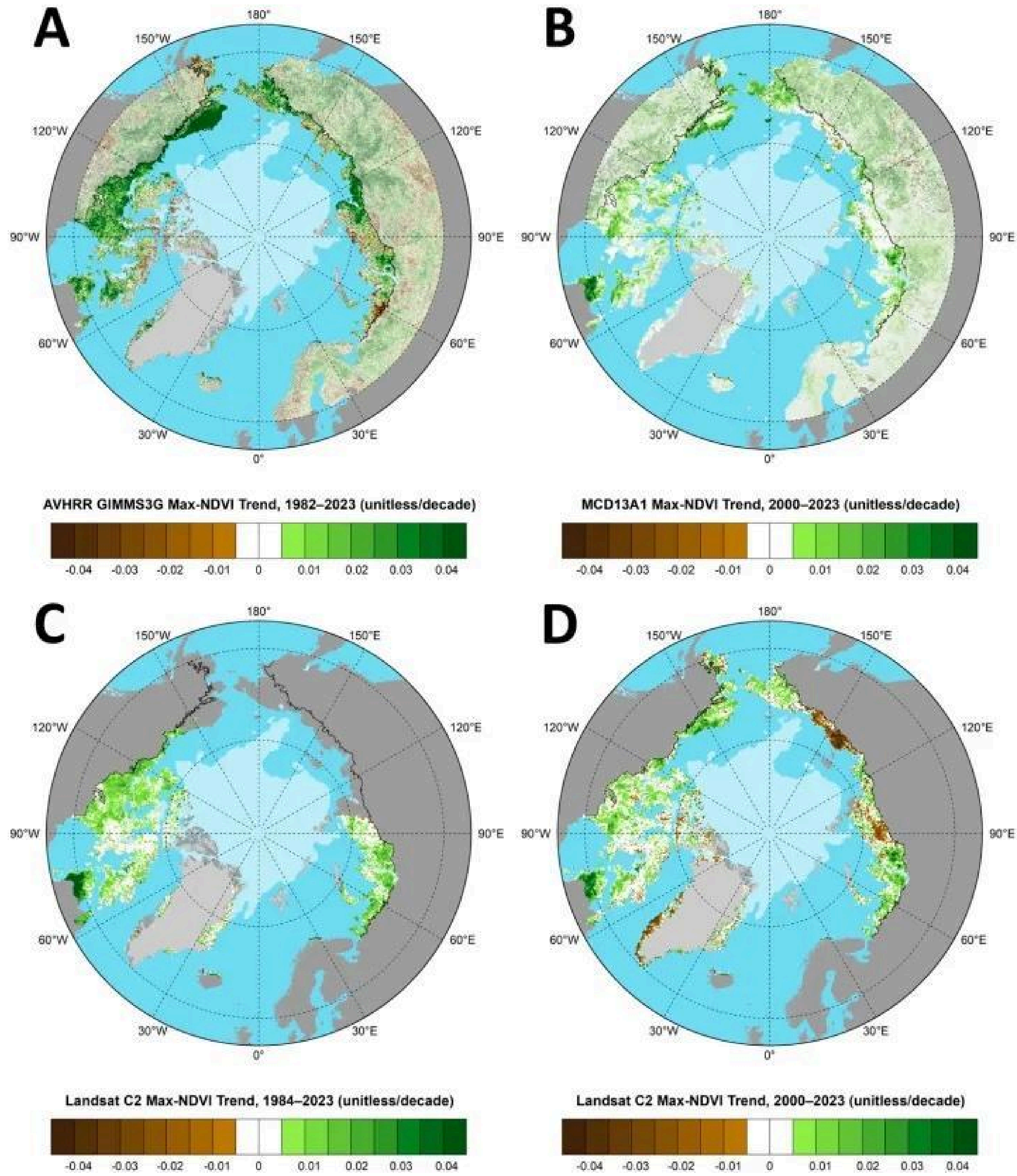
Thus, there is disproportionate warming in the landmass surrounding the Arctic, which, by its sheer size, accounts for two-thirds of the planet's greening over the last two decades. This represents an increase in leaf area on plants and trees equivalent to the area covered by all the Amazon rainforests. A third of the greening is occurring in China and India, while more than half is occurring at northern latitudes in the Northern Hemisphere. There are now more than two million square miles of extra green leaf area per year, compared to the early 2000s – a 5% increase.

Normalized difference vegetation index (NDVI)

With the availability of spaceborne observations of circumpolar tundra greenness, in the form of the Normalized Difference Vegetation Index (NDVI), there are now 40+ years of data and responses to climatic trends, variability, ecological disturbance, and successional processes. *Maximum NDVI* (MaxNDVI) is the annual maximum NDVI value observed during the period of peak phytomass in midsummer, typically in late July and early August for the Arctic. MaxNDVI is a strong indicator of above-ground biomass in tundra, making it particularly responsive to disturbance, successional processes, and long-term changes in vegetation structure. A time series of MaxNDVI through 2023 for the tundra domain of the Circumpolar Arctic Vegetation Map (Raynolds et al., 2019) from four sensors.

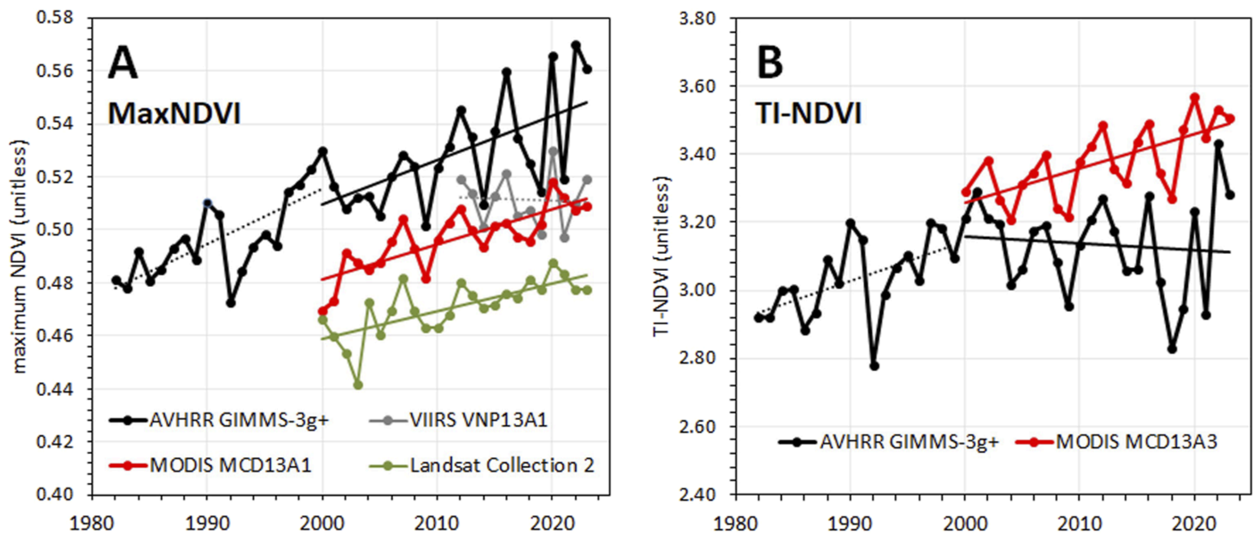
1. Advanced Very High Resolution Radiometer (AVHRR), 1982–2023, in the form of the Global Inventory Modeling and Mapping Studies 3 g V1.2 dataset (GIMMS-3g+) with a spatial resolution of 1/12° (~8 km) (Pinzon and Tucker, 2014; Pinzon et al., 2023).
2. Moderate Resolution Imaging Spectroradiometer (MODIS), 2000–2023, combining 16-day NDVI products from the Terra (MOD13A1, v. 6.1) and Aqua (MYD13A1, v. 6.1) satellites (Didan, 2021a; Didan, 2021b) with a spatial resolution of 500 m, hereafter referred to as MCD13A1. Pixels with a SummaryQA value ≥3 (indicating cloudy or otherwise compromised observations) were masked.
3. Landsat Collection 2 data, 1984–2023, derived from the Thematic Mapper, Enhanced Thematic Mapper, and Operational Land Imager sensors at a spatial resolution of 30 m. We use the approach of Berner et al. (2020) and Berner et al. (2023) to sample Landsat's coarse (non-daily) temporal resolution randomly. Time series plots are based on annual mean MaxNDVI values at sample pixels with ≥16 observations; observations were sparse in the early part of the record for Alaska and eastern Eurasia, so circumpolar trend analysis is only possible after 2000.
4. Visible Infrared Imaging Radiometer Suite (VIIRS), 2012–2023, using the 16-day VNP13A1 product from the Suomi National Polar-orbiting Partnership (S-NPP) satellite (Didan and Barreto, 2018) with a spatial resolution of 500 m.

All data were masked to exclude permanent ice and water.



Circumpolar MaxNDVI trends from **(A)** GIMMS-3g+ (1982–2023), **(B)** MODIS (2000–2023), and Landsat for **(C)** 1984–2023 (areas with sufficient data density only) and **(D)** 2000–2023. VIIRS trends are not shown due to the short period of record. Trends are shown in muted colors for the boreal forest biome south to 60° N (GIMMS-3g+ and MODIS only). All plots show the mean August 2023 sea-ice extent, and a thin black line indicates the treeline.

The first decade of AVHRR (Advanced Very High Resolution Radiometer) observations (Myneni et al., 1997) showed a wide latitudinal band extending well south of the Arctic tundra biome, with Arctic greening beginning in 1987 (see Figure below). This sequence was broken in 1992, due to transient Arctic cooling following the eruption of Mt. Pinatubo the previous year. Then there were consecutive record-high MaxNDVI values from 1997 to 2000. This was linked to rising land surface temperatures and declining spring and summer sea ice extent (Comiso, 2003; Comiso and Nishio, 2008; Bhatt et al., 2010). Shrub expansion quickly emerged as a likely ecological explanation for Arctic greening (Sturm et al., 2001),

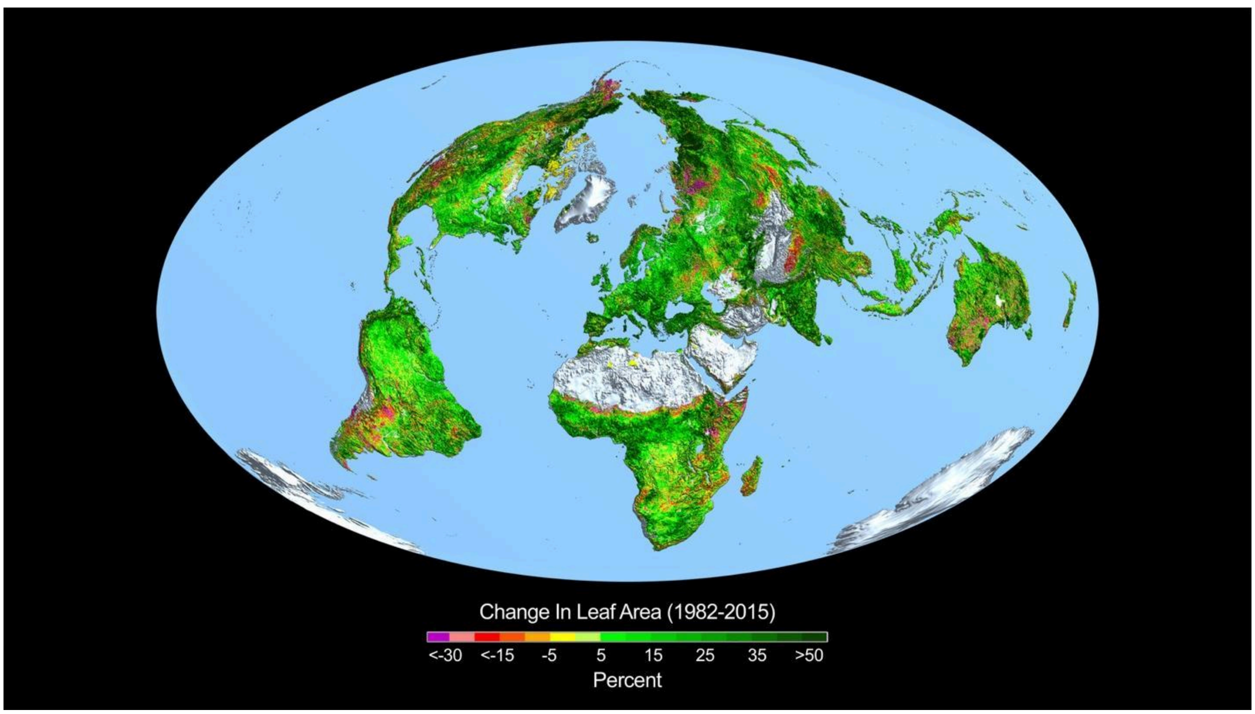


From the early 2000s to 2020, Arctic greening experienced a hiatus, with browning or stability. The year 2020 was a benchmark year for Arctic tundra greenness, with record-high circumpolar mean MaxNDVI values observed across all four satellite records (see figure above), and for TI-NDVI in the MODIS record from 2020 onwards. These records matched the years with record-high summer warmth over Arctic lands (see Climatic Drivers of Greening, below) and have continued the trend this decade. As glaciers retreat, new terrains are exposed to plant colonization and ecological succession. This is the beginning of a large-scale change in vegetation (both in plant cover and species composition) and in soil development. Moss colonization occurs at the initial successional stage within a few years of glacier retreat. Then, progressive accumulation of organic matter over decades provides substrate for colonization by vascular plants (which require a biological soil crust).

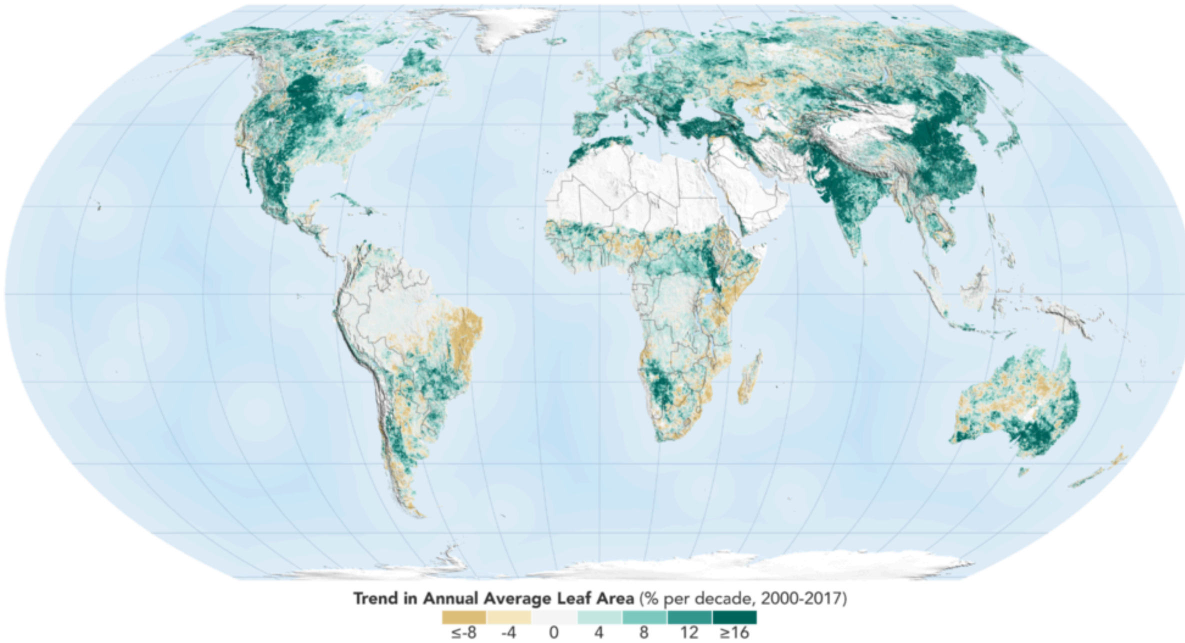
Climatic drivers of greening

Extended periods of open water are the main factor driving warming air temperatures along the Arctic Ocean coastline, which in turn promotes warmer onshore growing seasons that favor increased greenness (see Figure below). Open water (May–August average cover) and Summer Warmth Index (SWI, the sum of average monthly temperatures above freezing) have increased consistently since 1982, and circumpolar mean values have reached record highs during 2020–2023. 'Shrubification' is the key form of greening.

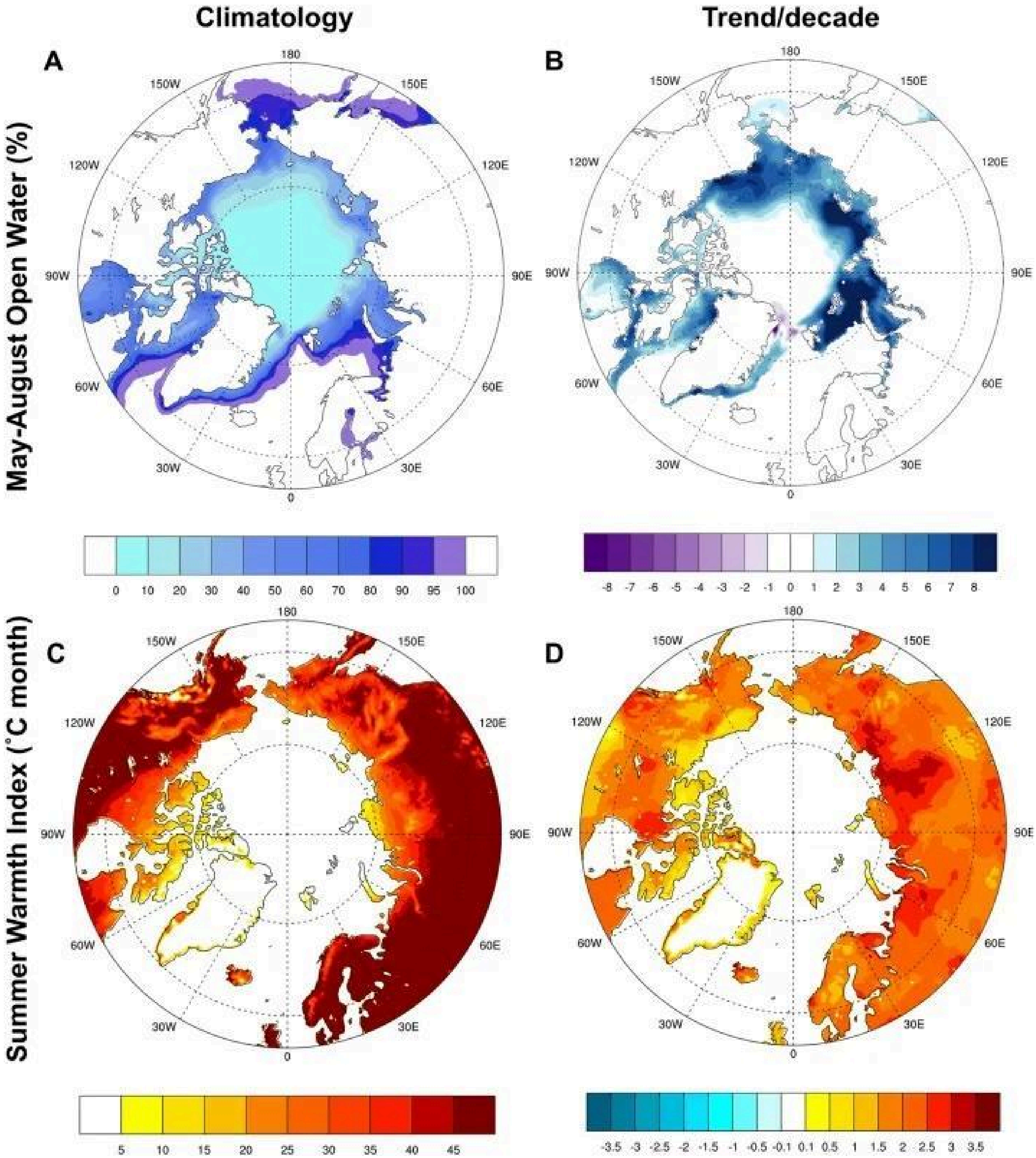
Permafrost is ground that has stayed at or below the freezing point of water—0°C (32°F) for at least two years. The combination of rising atmospheric and ground temperatures will lead to a deepening of the permafrost active layer thickness, which, in turn, will mobilize previously frozen soil nutrients that can now support further increases in biomass. Additionally, Arctic warming will accelerate decomposition and soil development, leading to increases in plant cover and biomass.



Credits: Boston University/R. Myneni



The world is a greener place than it was 20 years ago, as shown on this map, where areas with the greatest increase in foliage are indicated in dark green. Data from a NASA instrument orbiting Earth aboard two satellites show that human activity in China and India dominates the planet's greening.
u003cstrongu003eCredits: NASA/NASA Earth Observatory/Joshua Stevensu003c/strongu003e

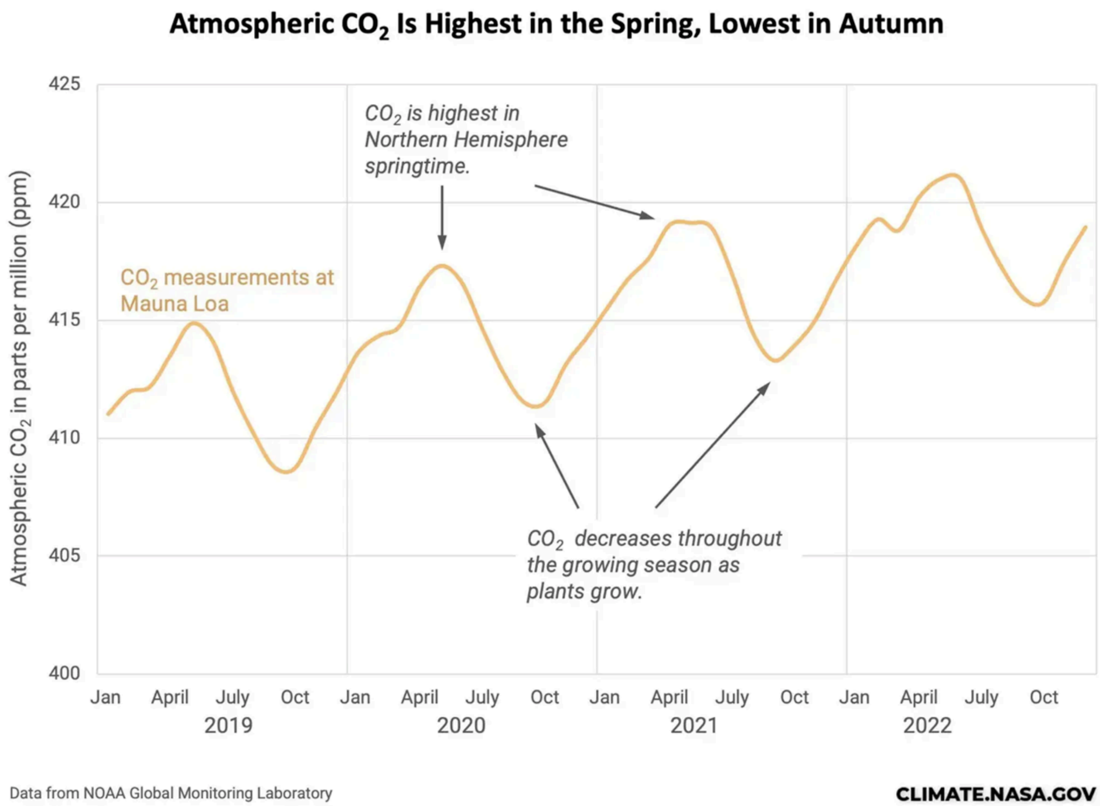


Climatology **(A)** and trend **(B)** of average May–August Open Water (% cover) based on passive microwave sea-ice observations, and climatology **(C)** and trend **(D)** of onshore summer Warmth Index based on ERA5 2 m-air temperature, 1982–2023.

CO2 as Fertilizer

Carbon dioxide is, in essence, the primary raw material for plant photosynthesis and is therefore an invisible ‘gas fertilizer’. As a direct carbon source, CO2 dramatically increases growth rates, increases crop yields, and improves plant resistance to environmental stress. Enriched CO_2 environments reduce stomatal conductance of water in leaves (Transpiration). This causes plants to require less water and minimizes soil moisture runoff. Carbon dioxide fertilization accounts for 70 percent of the greening effect on Earth, observed in the Arctic regions and the Amazon and Central African rainforests.

However, this fertilization effect is accompanied by a decline in essential nutrients, including proteins, iron, and zinc, in major food crops such as wheat and rice, a phenomenon known as CO2-induced nutrient dilution. This phenomenon threatens global nutrition by making *diets more caloric but less nutrient-dense*. The mean effect is −3.2% for all nutrients combined, but reaches up to 37.5% for zinc in chickpeas and a 31.7% increase for rubidium in soybeans. Rice is the primary staple crop for over half of the world's population, and another 2.5 billion people are dependent on wheat (Ebi et al. 2021). Both show significant decreases in essential nutrients, including protein (proxied by nitrogen), zinc, and iron. Decreasing nutritional value can have devastating health consequences, contributing to malnutrition, including in previously sufficient populations, by reducing nutrient availability even if food availability remains constant. It can contribute to hidden hunger, where people have sufficient food calorically but insufficient nutrients.



[NASA Earth is Greening Video]

CONCLUSION:

While increased plant growth absorbs more carbon dioxide, this benefit is outweighed by the massive release of greenhouse gases from thawing permafrost, making the Arctic a net carbon source. However, whether this is favorable depends on where one lives. In the northern half of the northern hemisphere, global warming has generally been a boon. At the same time, in the tropics, it is clearly a bane, with increasing droughts and hotter, more extreme, and more unpredictable weather.

"Glass Half Empty"

- **Permafrost Thaw:** Warming soils are melting permanently frozen ground, releasing vast amounts of trapped carbon and methane. This accelerates global warming in a positive feedback loop.
- **Vegetation Vulnerability:** While the overall trend is greening, certain boreal forests have experienced "browning" or die-offs due to droughts, wildfires, and insect outbreaks.

- **Albedo Loss:** As snow melts earlier and plants grow taller, the landscape absorbs more sunlight rather than reflecting it into space, driving further localized warming.
- **Nutrient Dilution:** may increase iron-deficiency anemia and protein malnutrition

"Glass Half Full"

- **More Vegetation:** Extensive satellite tracking from the NASA Landsat mission and ground-based studies by the NASA Science Team show a 7 to 10% overall increase in plant growth.
- **Longer growing season**: In Switzerland, the growing season has increased by around 30 days in the last 100 years. Similarly, in Canada, it's increased by 20 days (approximately 2 days/decade).
- **Wildlife Changes:** The expansion of shrubs and grasses provides increased food for specific herbivores, such as reindeer and caribou, altering local migration and foraging habits.
- **Soil Insulation:** Some tall shrubs and grasses accumulate a deeper, organic layer that can act as insulation, potentially slowing down the summer thaw of underlying permafrost.

Given the simple geographic fact that 50% of Earth's landmass is north of 30 degrees latitude north, positive impacts mentioned above are occurring in a much larger area than the negative impacts in the tropics, so will gains outweigh losses as a whole? to be determined.

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